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VOLUME XIII NUMBER 4

THE PHYSICAL REVIEW

A JOURNAL OF EXPERIMENTAL AND THEORETICAL PHYSICS

CONDUCTED BY

EDWARD L. NICHOLS

ERNEST MERRITT, and FREDERICK BEDELL

LXVIII

OCTOBER 1901

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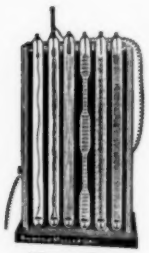

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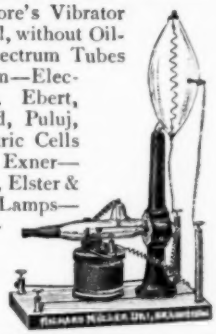

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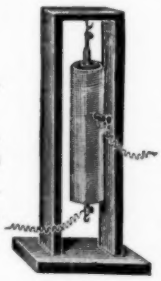

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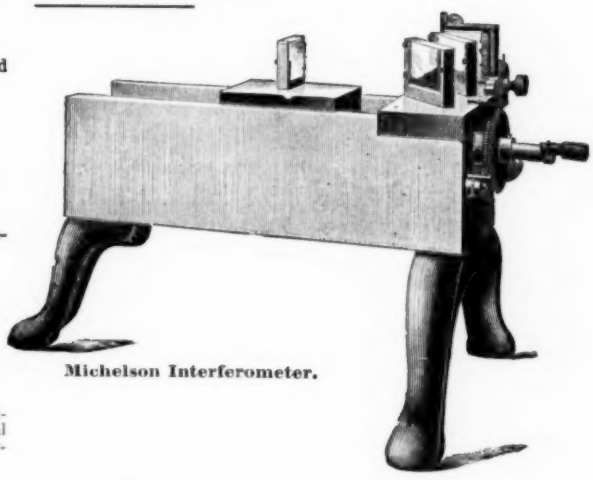

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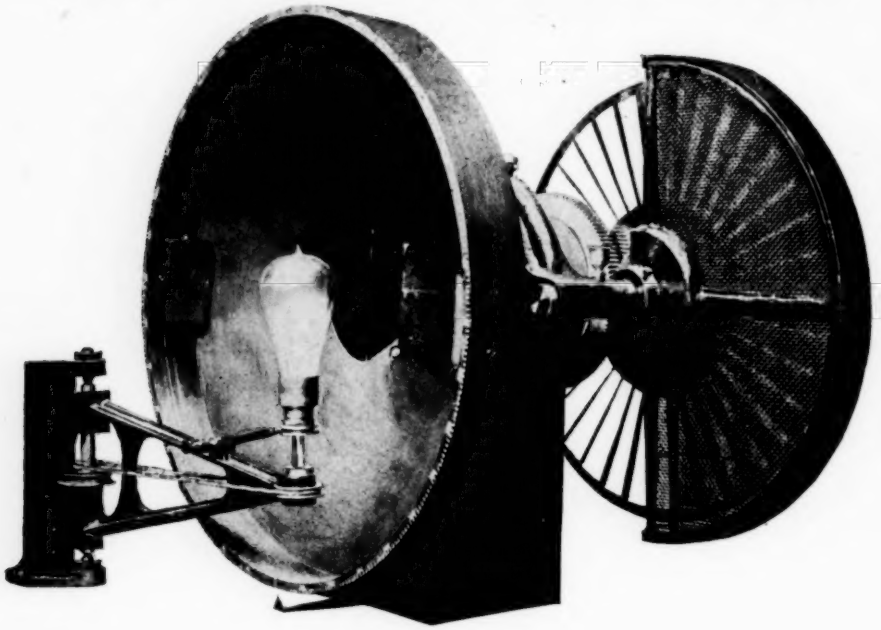

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THE

PHYSICAL REVIEW.

THE METALLIC REFLECTION OF ULTRA-VIOLET RADIATION.

By Perley Gilman Nutting.

SPECTRA reflected from such substances as glass, silver and benzene, that strongly absorb but part of the ultra-violet radiation, exhibit some very interesting peculiarities that have been but little studied. Langley[1] measured the reflecting power of silver out as far as wave-length 350 ($\mu\mu$), where it was 61 per cent., having fallen off very rapidly from nearly 80 per cent. at 400. Beyond the limit of Langley's observations we have found that the reflecting power falls off still more rapidly to a rather sharp minimum of less than 10 per cent. between 320 and 324. Glatzel[2] has observed this minimum. Corresponding with this reflection minimum is a very pronounced transmission band, the spectrum between wave-lengths 310 and 340 being quite freely transmitted by a coating of silver on quartz so thick as to completely absorb all other radiation between 800 and 185. If then all the radiation in this region were visible, silver would possess a very strong surface color, transmitting only those waves which it does not reflect. Strong reflection minima of this form are difficult of theoretical explanation. Nor do any of the other ten metals examined exhibit this peculiarity. Beyond this minimum the reflecting power of silver increases again to about 30 per cent. at about wave-length 250 and then falls off again to less than 10 per cent. at 185. Silver then, at normal incidence, reflects but little better than many crystalline salts in at least two spectral regions, and in these regions its reflecting power

[1] S. P. Langley, Phil. Mag., 27, 10, 1889.

[2] B. Glatzel, Phys. Zeitschr., 2, 173, 1900; Beibl., 25, 35, 1901.

could hardly be termed metallic. On the other hand, the reflecting power of other metals, notably mercury, remains high and nearly constant, falling off but slightly in the neighborhood of wave-length 185.

The reflecting power of solid cyanin is interesting in view of its well-known strong and narrow absorption band in the optical region, and its suspected second band in the ultra-violet. Wood and Magnusson[1] have recently determined its refractive index through the first band and predicted the existence of the second from the form of the index curve in its neighborhood. In the region of the first band the reflecting power of cyanin is well up among those of the metals, in excellent agreement with its value calculated from the refractive and absorptive indices; but in the region of the ultra-violet band, the reflecting power appears to follow quite a different law.

Such substances as glass and many of the crystalline salts and hydrocarbons, which strongly absorb the shorter waves, have been examined with a view to testing Drude's and Beer's formulas for the reflecting power of absorbing substances. According to each of these formulas, the reflecting power should be large when the absorptive indices are large. Their disagreement with observed phenomena indicates an absorption not due to molecular resonance or to the electrical conductivity of particles imbedded in a dielectric. On the other hand, the great reflecting power of the benzines in the ultra-violet, where they have so many strong absorption lines, [2] is in close agreement with the above reflection formulas. Carbon bisulphide, with its narrow, well-defined transmission band in the extreme ultra-violet, is a particularly good subject for study.

Again, the volatile petroleum ethers and napthas, absorbing all waves beyond 280, offer a striking contrast to dense, viscous glycerine which absorbs little or nothing out as far as wave-length 185, yet the reflection spectra of all these substances do not materially differ beyond 300. The compound distillation products of petroleum suggest, by their behavior, another possible field for the existence of metallic reflection. The series of products with increasing boiling points possesses the remarkable property of alternately absorbing and transmitting that part of the spectrum extending from

[1] Wood and Magnusson, Phil. Mag. (6), 136, Jan., 1901.

[2] See Pauer, Wied. Ann., 61, 367, 1897.

near the visible out to 185 $\mu\mu$. Napthas of increasing boiling points from 80° to 130° show a slightly increasing absorption. Kerosene, with a slightly higher boiling point, does not absorb at all. Paraffin oil, next in the series, absorbs moderately and uniformly from near the visible to 185 mm. Vaseline, fluid at about 50°, can scarcely be distinguished from paraffin oil, yet it strongly absorbs all the spectrum from near the visible. Finally pure paraffin, fluid at about 80°, is again a non-absorber. Not only was there no trace of metallic reflection from the partially absorbing members of this series, but neighboring members had reflecting powers as nearly alike at 200 as in the optical region.

Metallic reflecting power might be looked for in the ultra-violet in the case of fluorescing substances like uranium glass, common glass and the heavier members of the paraffin series. Nearly all glasses, particularly the harder varieties, fluoresce strongly in the region of the four zinc lines between 200 and 210, much more strongly than in regions of greater or less wave-length. The reflecting power of these substances has been examined with especial care in this region.

Apparatus and Method.

The methods employed have been purely photographic. The intensity of the radiation was taken to be inversely proportional to the time necessary to bring two exposures to the same density, provided certain precautions were observed. A number of brands of plates were first tested for this proportionality. Each was exposed, in adjacent squares, to a very short spark having a large capacity in parallel so as to be nearly non-oscillatory, a single spark at 25 cm., four sparks at 50 cm., sixteen sparks at 100 cm. The photometric sensitiveness of the plates was tested by making exposures of 15, 16 and 17 sparks side by side. Cramer's isochromatic plates were found to be thoroughly satisfactory for photometric work and very sensitive to the extreme ultra-violet. Seed and Lovell plates, particularly the smaller commercial grades, could not be used with success. The use of photography in photometry depends primarily upon the bringing out of slight differences in the photographic impressions. Plates must be considerably under-ex-

posed and completely developed with a rather slow developer. Much depends upon the kind of developer used. What are known as "contrasty" developers are best. We find the ordinary metol-hydrochinone to be entirely satisfactory when diluted to one-fourth strength and used fresh each time.

As a source of radiation, an induction coil spark was used between terminals of an alloy of about two parts aluminum to one of zinc. This alloy gives an excellent spectrum to work with, the whole region from the visible to the extreme aluminum line at 185 being filled with lines of very nearly the same intensity very evenly distributed. This alloy possesses the further advantage of being very durable, much more so than either metal alone. The spark was completely enclosed, but for the slit, within a short brass tube of about five cm. diameter having one cap of wood for holding the inner electrode. The spectrum lines themselves being entirely unsuitable for photographic photometry, a capacity of seven large Leyden jars was placed in parallel with the spark so that the spectrum was quite continuous between the lines. The interrupter on the coil was refitted and adjusted until it would run continuously for hours without perceptible variation in the intensity or frequency of the spark.

For accurate photometry, the two spectra to be compared must be brought to exactly the same focus. Faint lines, slightly out of focus, do not appear at all on the negative. A corresponding weakening appears through the whole spectrum so that great care is necessary in adjusting the reflecting surfaces.

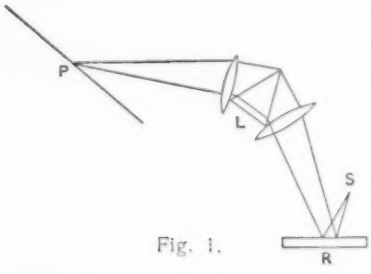


Fig. 1.

Fig. 1 shows the arrangement of the apparatus used in the greater part of the work. Radiation downward from the horizontal spark *S* is reflected upward at nearly normal incidence from the reflecting surface *R* through the quartz spectrometer train *L*. The reflecting surface rested upon a plane-faced, massive block of metal. An absorbing plate or quartz cell of an absorbing liquid could be inserted between the reflecting surface and the first lens. A plate holder of

special design at P was inclined at an angle of about 45° so that all parts of the spectrum were in focus upon a fluorescent screen within it. After the first exposure, the plate holder was displaced laterally in its own plane by a mechanical device and another exposure made close beside the first. For a known standard reflector for comparison a quartz plate was used, set in a brass block and backed with a mixture of balsam, boneblack and turpentine to prevent reflection from its lower surface. Photographic plates about three by twelve centimeters were used and on each plate three exposures were made, one of reflection from quartz and two from the substance under examination. The time of exposure was determined by means of a metronome beating seconds. Exposures varied from ten to fifty seconds.

Discussion of Results.

Silver.—Two silver reflectors were used, one freshly deposited from Rochelle salt silvering solution and the other a piece of mirror plate from which the covering had been removed with carbon bisulphide. The surfaces used in the determination of the reflection curves were lightly polished with a clean, dry, bristle buffing wheel. Unpolished coatings of silver and quartz backed with silver gave the same minimum in their reflection spectra. About sixty exposures were made in the determination of the curve. The accompanying photograph (see Plate I.) shows the transmission band corresponding with the reflection minimum. The faint transmission in other regions is probably due to a few pin holes remaining in the silver coating. The (lower) transmission spectrum was exposed for two minutes, mercury being used for the lower reflector. The middle spectrum is the direct reflection from the mercury—exposure two seconds. The upper spectrum is reflected from silver—exposure twelve seconds. Beyond wave-length 200, silver is by far the poorest reflector of the metals studied and its reflection can hardly be called metallic.

Gold.—Gold foil was pressed between two glass plates, on one of which was a thin coating of warm sealing wax. The surface was rather dull with a reflecting power nearly constant throughout the whole spectrum.

Lead and Cadmium.—Small blocks of these metals were shaved clean of impurities and pressed against plate glass in a vise. Excellent optical surfaces were obtained in this manner. The reflect-

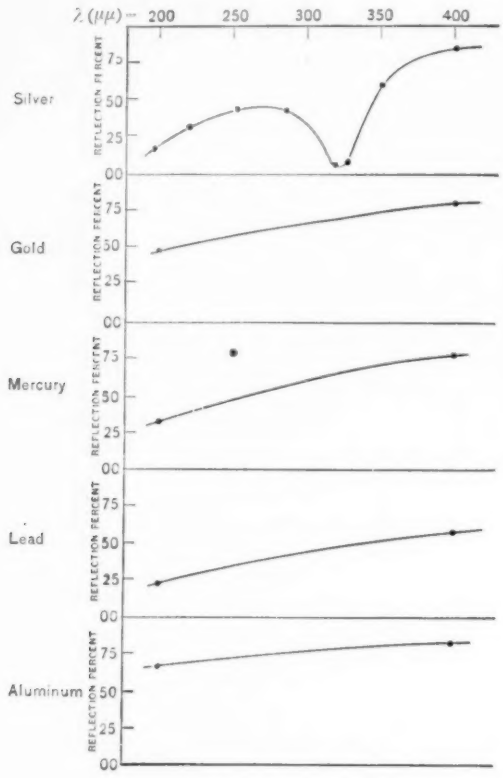


Fig. 2.

ing power of these substances is nearly constant, falling off slightly in the region of extremely short waves.

Mercury, distilled and free from grease, showed a reflecting power high and constant.

Aluminum, *zinc*, *copper* and *brass* were polished dry on a clean oil stone of very fine grain and gave fairly good optical surfaces with very constant reflecting power.

Grating Metal.—The spectrum was reflected from the polished surface bordering the rulings of a small plane grating. The reflecting power falls off considerably in the region of the shorter waves.

The reflecting power of these metals is shown graphically in Figs. 2 and 3.

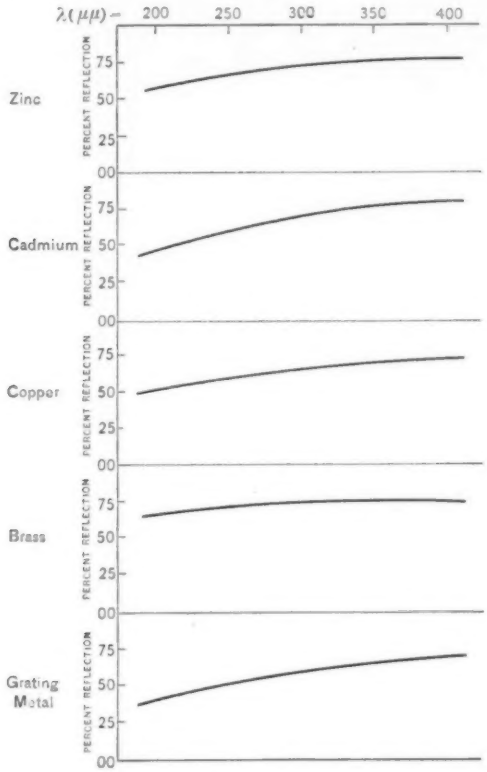


Fig. 3.

Glass.—Ordinary French plate and mirror plate, from which the silver had been removed, were used. Both were backed with Canada balsam and boneblack to avoid reflection from the lower surface. Glass shows strong absorption beginning abruptly, even when layers but half a millimeter thick are used. The reflecting power, however, remains constant in this region in which the absorption begins so abruptly and has a constant ratio to that of quartz from the visible to the extreme end of the spectrum at 185. According to Drude's formula for reflection[1] we should have for the reflecting powers at wave-lengths 350 and 400, the anomalous relation

[1] Drude, Lehrbuch der Optik, Leipzig, 1900, p. 336.

$$\left[\frac{n^2(1+\varkappa^2)+1-2n}{n^2(1+\varkappa^2)+1+2n}\right]_{\substack{\lambda=350\\ \chi=20}} = \left[\frac{n^2(1+\varkappa^2)+1-2n}{n^2(1+\varkappa^2)+1+2n}\right]_{\substack{\lambda=400\\ \chi=0}}.$$

Glass certainly does not show metallic reflecting power in the region in which its absorption is very great. Its properties in this respect are like those of solutions. An alcohol solution of cyanin for example, strongly absorbing all the ultra-violet, shows a low and

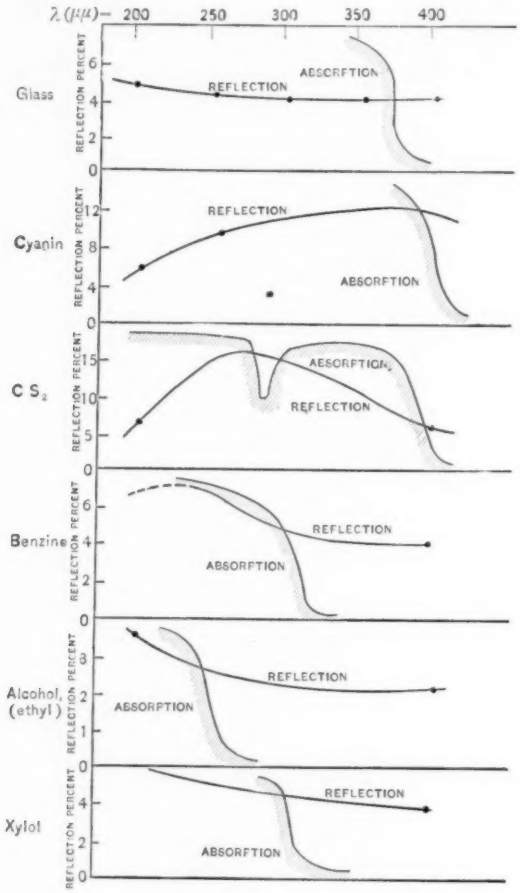


Fig. 4.

nearly constant reflecting power, practically the same as that of pure alcohol. The lack of metallic reflecting power in the case of

glass may be explained if we consider it a solution of absorbing salts in a non-absorbing silicate solvent. No variation in reflecting power could be detected in the regions of strong fluorescence either of common glass or of uranium glass.

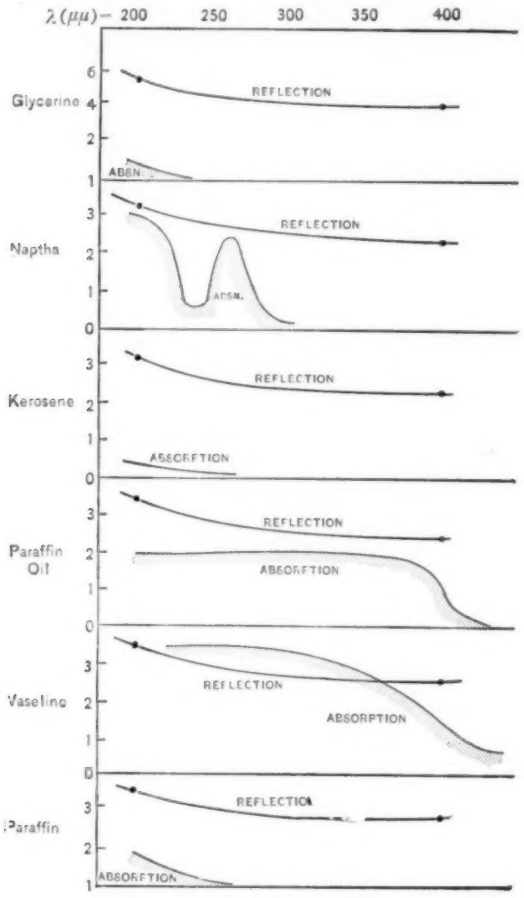


Fig. 5.

Cyanin.—Excellent plane mirrors were obtained by fusion of cyanin between plates of glass after the method used by Wood for making thin prisms. When one plate is quartz, the results are better, as the glass usually comes off clean, leaving the cyanin unbroken on the quartz. The accompanying photograph, in Plate II., shows the second absorption band covering the whole ultra-violet beyond

380. The reflecting power is considerably increased in the region of the absorption, but could hardly be called metallic.

Carbon Bisulphide.—The absorption region covers the whole ultra-violet beyond 380, with the exception of a narrow transmission band between 280 and 290. The reflecting power is somewhat increased in this region.

Benzine.—Pauer[1] obtained numerous narrow bands with very thin layers of benzine in the region in which the photograph shows the absorption of a layer 1.5 mm. thick to be complete. The ultra-violet lines of benzine vapor show every characteristic of molecular resonance, and the very considerable reflecting power in this region is additional evidence of such a mechanism of absorption.

Alcohol, xylol, glycerine and the petroleum products show more or less absorption but give no indication of metallic reflection. The curves for these and the preceding substances are given in Figs. 4 and 5.

BERKELEY, CAL., April, 1901.

[1] J. Pauer, Wied. Ann., 61, 368, 1897.

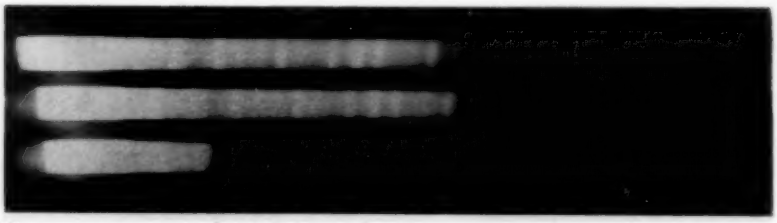
SILVER I.

Upper spectrum reflected from silver.
Middle spectrum reflected from mercury.
Lower spectrum transmitted through a thin sheet of silver on quartz.

SILVER II.

Upper spectrum reflected from quartz.
Middle and lower spectra reflected from silver.

GLASS.



Upper spectrum reflected from glass.
Middle spectrum reflected from quartz.
Lower spectrum transmitted through plate glass.

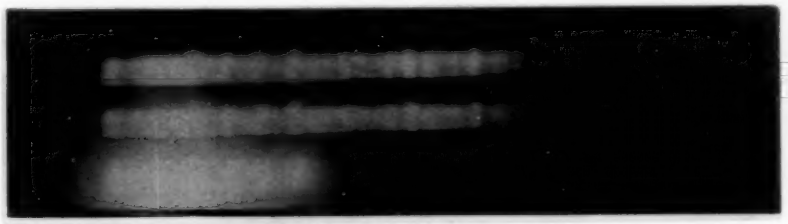
CYANIN.

Upper spectrum reflected from cyanin mirror.
Middle spectrum reflected from quartz.
Lower spectrum transmitted through ½ mm. of alcoholic solution of cyanin.

CARBON BISULPHIDE.

Upper spectrum reflected from Carbon Bisulphide.
Middle spectrum reflected from quartz.
Lower spectrum transmitted by thin layer of Carbon Bisulphide.

BENZINE.



Upper spectrum reflected from benzine.
Middle spectrum reflected from quartz.
Lower spectrum transmitted by a thin layer of benzine.

ON THE MAGNETIC EFFECT OF ELECTRICAL CONVECTION.

By Harold Pender.

Historical Review.

FROM a series of experiments extending over the last four years, M. V. Cremieu [1] has come to the conclusion that a moving electrified body produces no magnetic effect. The conclusion is in direct opposition to the classical experiment performed by Professor Rowland [2] in Berlin in 1876, which was subsequently repeated in this laboratory by Professor Rowland and C. T. Hutchinson [3] in 1889, and confirmed also by experiments performed by Röntgen [4] and Himstedt [5] in Germany. A further investigation of this very important question was therefore considered desirable. Accordingly in the fall of 1900, under the supervision of Professor Rowland, the following research was undertaken. As a result it is has been shown conclusively that electrical convection does produce magnetic action.

The idea that a moving electrified body might produce a magnetic effect similar to that produced by an electric current first occurred to Faraday [6] in 1837. The first to perform an actual experiment on the subject, however, was Professor Rowland. The experiment was carried out in Germany in 1876, though the idea of it had occurred to him as early as 1868, and is recorded in a notebook of that date. His method was similar to that described by

[1] C. R., T. 130, p. 1544, 1900; T. 131, p. 578 and p. 797, 1900; T. 132, p. 327 and p. 1108.

[2] Pogg. Ann., 158, p. 487. Am. Jour. Sci., 1878, p. 30.

[3] Phil. Mag., 27, p. 445, 1889.

[4] Ber. d. Ber. Akad., 1885, p. 195.

[5] Wied. Ann., 38, p. 560, 1889.

[6] Exp. Res., Vol. I., art. 1644.

Maxwell in his Treatise on Electricity and Magnetism (§ 770), written presumably in 1872 or 1873.

In the Berlin experiment, Professor Rowland used a horizontal hard rubber disc (diameter 21 cm.) coated on both sides with gold, revolving between two glass plates with their inner surfaces also gilded. Each side of the disc formed a condenser with the gilded surface opposite it. The condensing plates were earthed; and the disc charged by means of a point brought up within ⅓ mm. from the periphery. An astatic needle was suspended above the upper condensing plate, so that its lower magnet was nearly over the edge of the disc, and perpendicular to a radius of the same. The needle was enclosed in a metal case, so as to screen it from electrostatic action. The speed of the disc was 61 revolutions per second. On reversing the sign of electrification of the disc, a deflection of from 5 to 7.5 mm. was obtained, depending on the conditions. The deflection was the same whether the gilded surfaces of the disc and condensing plates were divided into sectors, or left continuous. The deflection as observed and calculated agreed quite well, but as the needle was always very unsteady, it was impossible to make the readings with great accuracy. In 1883 Lecher[1] repeated Rowland's experiment, but obtained negative results. Only a short account of this investigation was published, no details of the apparatus being given. It is impossible, therefore, to say why he obtained no effect. It may have been because his apparatus was not sufficiently sensitive.

In 1885, in an attempt to detect the existence of displacement currents, Röntgen[2] had occasion to use an apparatus similar to that employed by Professor Rowland in his Berlin experiment. The ebonite disc in this case was not covered with gold. Incidentally, the effect on the suspended needle of charging the disc, when rapidly rotating, by a brush discharge from a series of points, was tried. The Rowland effect was readily observed. On reversing the sign of electrification a deflection of from 8 to 10 mm. was noted. In 1888[3] this apparatus was again used to investigate the

[1] Rep. d. Phys., 20, p. 151, 1884.
[2] Sitzb. d. Ber. Akad., 1885, p. 95.
[3] Sitzb. d. Ber. Akad., 1888, p. 23. Wied. Ann., 40, p. 93.

action of a dielectric moving in a homogeneous electrostatic field. If the upper condenser plate is charged negatively (say) and the lower positively, then there will be an apparent positive charge on the upper surface of the disc, and an apparent negative charge on the lower surface. If then the motion of an apparent charge due to the polarization of the dielectric produces magnetic action, the needle, which was nearer the upper than the lower surface, ought to show a deflection on rotating the disc and charging the condenser formed by the two stationary plates. After all precautions had been taken to prevent the disc from assuming a real charge, a deflection of from 2 to 3 mm. was observed on reversing the sign of electrification of the condenser plates.[1] On increasing the difference of potential between the condenser plates until a brush discharge took place between the upper plate and the disc (the upper plate was .14, the lower .25 cm. from the disc) the Rowland effect was again readily observed.

In 1889 Professor Rowland and C. T. Hutchinson[2] repeated in this laboratory the original Berlin experiment, employing, however, a different form of apparatus. Instead of a single disc rotating in a horizontal plane, they used two vertical discs rotating about horizontal axes in the same line; the needle system, enclosed in a brass tube, was placed between the discs, opposite their centers. Each disc was surrounded by a guard ring, both discs and guard rings being gilded on the side facing the needle. Between the discs were placed two condensing plates—glass plates gilded on the surfaces facing the discs. Between the condensing plates was suspended the needle. This arrangement permitted of accurate calculation of the effect which should be expected. The condensing plates were charged from a Holtz machine and battery of Leyden jars, to a potential of about 5,000 volts; the discs were earthed by means of metal brushes bearing on studs fixed in the periphery of the discs. The speed of the discs was about 125 revolutions per second.

[1] Röntgen gives no calculation of the effect which should be expected. On the assumption that the magnetic force due to any element of surface is proportional to the quantity of apparent charge passing a given point in unit time, I have calculated from the data given in Röntgen's paper that the deflection should be 2.1 mm. I employed the formulæ used by Rowland in his Berlin experiment (loc. cit.).

[2] Phil. Mag. (5), 27, 445.

The deflection of the needle on reversing the electrification was from 5 to 8 mm. This experiment offers a means of determining the ratio of the two systems of electrical units. The mean of all their determinations gave for this 3.19×10^{10}; the determinations which differed from this the most being 3.74×10^{10} and 2.26×10^{10}.

During the same winter of 1889 Himstedt[1] carried out a series of experiments on this subject in Giessen. In his first experiments he employed the same apparatus as had been previously used by Röntgen, with some modification in details. Later on, apparatus was constructed similar to that used by Rowland and Hutchinson, but considerably more sensitive. Discs of ground glass 20 cm. in diameter were mounted so as to revolve about horizontal axes in the same line. A strip on the edge of both sides of the discs was made conducting by rubbing into the ground surface a thin coat of graphite. On both sides of each disc were placed condensing plates, and between the two inside plates was suspended an astatic needle, properly shielded, the upper needle being just above, the lower just below the conducting strip. The discs were charged by an induction machine and a battery of Leyden jars by means of a sliding contact. With a speed of 117 revolutions per second and discs charged to 5,000 volts (condenser plates earthed), a deflection of 100 mm. on a scale 3 m. distant was obtained on reversing the sign of electrification of the discs. This apparatus did not permit of ready calculation of the deflection to be expected, so no absolute measurements were made. Himstedt, however, showed that the deflection was in the direction to be expected, reversed with the direction of rotation of the discs, was proportional to the speed of rotation, and for the disc at potentials of from 400 to 4,000 volts was proportional to the surface density of the charge on the disc. Above 4,000 volts this latter proportionality ceased to exist, the deflection remaining approximately constant up to the highest potential tried 14,000 volts. Himstedt explains this by assuming that there is a limit to the amount of charge which a moving body can carry with it. For these high potentials, however, the leakage was considerable; in one minute the potential dropped from 14,000 to 4,000 volts. Any theoretical conclusion of the above nature must therefore be accepted with reserve.

[1] Wied. Ann., 38, p. 560, 1889.

So stood the question as to the existence of a magnetic action due to electric convection in 1897, when Cremieu began his experiments. The first problem[1] attacked was the reverse of the above experiments, viz., the detection of the mechanical force exerted on a charged body by a rapidly changing magnetic field. This quantity is extremely small, varying as the reciprocal of the square of the ratio of the two systems of electrical units. Cremieu attempted to detect this force by the rotation of a charged aluminium disc suspended between the poles of a strong electromagnet. No deflection of the disc was observed, though the calculated deflection as read by means of a telescope and mirror on a scale 1.1 m. distant was 100 mm. This is in direct opposition to Lodge's experiment[2] on the same subject performed in 1889, though Lodge's experiment is not altogether satisfactory, as the observed deflection was only from 2 to 3 mm. Cremieu has published only a short note on this experiment, with no details of the apparatus, so that it is impossible to discuss the work further.

The negative results obtained from the reverse experiment led Cremieu to investigate once more the magnetic action of a moving electrified body.[3] A very ingenious method, distinctly different from any of those previously employed, was used. A solid aluminium disc, 37 cm. in diameter, was mounted on an insulating hub of hard rubber turning on a horizontal axis. Concentric with this disc was placed a coil of 13,000 turns of copper wire .15 mm. in diameter, connected in series with a sensitive galvanometer. The diameter of the coil was 44 cm. The coil was enclosed in a brass case. The disc revolved between two thick iron condensing plates. These plates also served to decrease greatly the reluctance of the magnetic circuit through the coil. The whole distance from plate to plate was 8 mm., the disc revolving in the center of this opening. A brush rubbing on a brass ring mounted on the insulating hub and connected to the metal disc, served to connect the disc with one terminal of a high potential battery (5,000 volts), the other terminal of which was earthed. On charging or discharging the disc, the

[1] C. R., 131, p. 578, 1900.
[2] Phil. Mag. (5), 27, p. 469, 1889.
[3] C. R., 130, p. 1544, 1900.

condensing plates being earthed, on the assumption that a moving charge produces a magnetic action, a current should be induced in the coil, and the needle of the galvanometer deflected. The calculated effect of a single charging or discharging was too small to be detected, so that a combined interrupter and commutator was employed. This instrument served to charge and discharge the disc a number of times a second, and at the same time to commutate any alternating current (if there was any) which might have been induced in the coil. The galvanometer should therefore have shown a permanent deflection if the commutator was kept running at a constant speed. No such deflection was observed, though the calculated deflection was from 20 to 50 mm.

Four series of experiments were performed. In the first was used a solid aluminium disc 0.5 mm. thick. This was charged to 5,000 volts, but it immediately discharged itself by sparks across the small gap between the disc and condensing plates. To prevent this, the latter were covered with glass plates, lacquered, 2 mm. thick. This, however, left a space of only 1.75 mm. between the disc and glass surface. It was suggested by Pellat that perhaps the charge brushed across from the disc to the glass surface, thus leaving the disc uncharged. This was tested by Cremieu for *the disc at rest*, and found not to be the case. But it is impossible to make a disc of aluminium only 0.5 mm. thick and 37 cm. in diameter, run perfectly true at a speed of 100 revolutions per second. Consequently, when the *disc was rotating*, the interval between it and the glass surface must at certain points have been considerably less than 1.75 mm., and therefore the above objection still holds. This is the explanation of the negative results of Cremieu's experiments which was given by Professor Rowland.

In his second series ef experiments Cremieu used an aluminium disc 1 mm. thick, covered with a thin coating of caoutchouc, the condensing plates being left bare. Again negative results were obtained. When it is remembered that the distance between the disc and the condensing plates was only 3.5 mm., and that an aluminium disc of the diameter used, even though 1 mm. will not run perfectly true, it seems by no means improbable that there may not have been a brushing over of the charge from the condensing

plates to the caoutchouc surface. The magnetic action of this charge would then just neutralize that of the charge on the disc. This same objection applies to the third series of experiments, in which was used an ebonite disc 2 mm. thick, gilded on both sides in three sectors and covered with caoutchouc; and to the fourth series, in which the iron condensing plates were covered with sheets of mica, over which was pasted tin foil in six sectors, covered with a thin layer of caoutchouc. (The object of the third and fourth series was to see if the negative results were due (1) to the slipping of the charge with respect to the disc, or (2) to the movement of the charge induced on the condensing plates with the inducing charge on the disc.)

During the past winter Cremieu has continued his investigations,[1] replacing the coil and galvanometer by an astatic needle, and again with negative results. The rotating apparatus consisted of the same ebonite disc, mounted in a bronze frame of the same dimensions as the iron frame previously used. To this frame were screwed brass plates, covered with mica, and over the latter was pasted tin foil in six sectors, connected to the earth. The astatic needle was placed outside of these, with the lower needle opposite the upper edge of the disc. To this experiment applies the same objection as to those previously performed, viz., the rotating disc probably did not keep its charge. It is interesting to note that in a second series of experiments with this apparatus, in which the tin foil was mounted on ebonite plates and these screwed directly to the bronze frame, so that between the needle and disc there was only one metal plate, a deflection was obtained, in the proper direction and reversible with the sign of the electrification of the disc and the direction of rotation. This Cremieu states was suppressed by the introduction of a brass plate between the needle and the condensing plates. Without a more detailed account of the exact conditions under which this effect was obtained than is given by Cremieu, it is difficult to say exactly what this means.

Believing that the deflection observed by previous investigators might have been due in some way to the condensing plates, a different arrangement was then employed.[2] The same ebonite disc,

[1] C. R., 131, p. 797, 1900.
[2] C. R., 132, p 327, 1901.

with the three sectors completely insulated from one another, was again used, but the condensing plates formed by tin foil on ebonite were each divided in half. The lower half of each was put up close to the disc (how close Cremieu does not state); the upper halves were 10 mm. distant. The foil covering a sector of 60° on each of the upper halves was removed. The needle, enclosed in a copper tube with walls .4 mm. thick, connected to the earth, was placed directly over the edge of the disc opposite this break in the condensing plates. Each sector of the disc was charged when immediately between the lower halves of the condensing plates. When it came under the needle it was completely insulated from the other two and from the charging apparatus. With this apparatus Cremieu again found that no deflection of the needle was produced on charging or discharging the rotating discs, so long as the needle was properly screened against direct electrostatic action. If, however, the copper tube above mentioned was replaced by a tube of some less perfect conductor, *e. g.*, graphite paper, a deflection could be obtained, which had all the characteristics expected of an effect due to electric convection. But this effect could be obtained equally well when the magnets forming the astatic needle were removed and only the mica vanes on which they were mounted were left. Here are Cremieu's final conclusions:

"Enfin, toutes les fois que le système suspendu, quel qu'il soit, est protégé par un écran électrique très conducteur, on ne peut obtenir aucune déviation.

"De plus, il arrive souvent qu'au moment où l'on change le signe de la charge du disque, une étincelle, ou même une sorte de pinceau de décharge à peine lumineux, se produit entre le disque et les plateux fixes.

"Ceci cause, sur l'aiguille aimantée, des impulsions réversible a la fois avec le signe de la charge et le sens de la rotation, le peu de stabilité du zéro de systèmes aussi sensibles fait qu'il peut résulter de ces impulsions des déviations permenentes faibles."

According to Cremieu's explanations of these slight deflections there is no reason why they should reverse with the direction of rotation of the disc. In all probability, however, these deflections were really caused by electric convection, and should have reversed

as observed. Though in the short note which Cremieu has published concerning this experiment there is no mention made of a caoutchouc coating over the disc, the disc was undoubtedly thus covered as in all the previous experiments. The sparks observed were then due to the passage of the charge from the condensing plates to the caoutchouc surface. A slight charge might still have remained on the condensing plates, so that the charge taken by the caoutchouc surface was less than that on the surface of the disc. The slight deflection observed was, probably, then really due to the difference in magnetic action of these two surfaces. It is also seen why a deflection of the magnitude expected was not obtained.

If Cremieu's conclusions are true, then "open currents" can exist. Cremieu has tested this deduction by the following experiment.[1] An ebonite disc, 37 cm. in diameter and 2.5 mm. thick, was gilded (presumably on one side, if one may judge from the diagram given) in 25 sectors, the distance between sectors being 1 cm. This disc turned about a horizontal axis between two fixed ebonite plates. One of these plates (presumably the one facing the side not gilded) carried a sector of tin foil twice as wide as the sectors on the disc. On the second plate, opposite this sector was fixed a brush which made contact with the sectors on the disc when immediately under the fixed sector. This brush was also connected to a second brush on the same plate, about 60° ahead of the first brush. Then, according to Cremieu, if the fixed sector is connected to a source of electricity and the disc set rotating, each sector, as it comes under the fixed sector, will receive a charge by induction; when this sector makes contact with the second brush it will be discharged. There will then be a conduction current flowing in the wire connecting the discs, which circuit is completed by the charge carried convectively between the two brushes. An astatic system was suspended with its lower needle near the edge of the disc, between the two brushes. The conduction circuit between the two brushes contained a galvanometer. The fixed sector was charged to a potential of 100 to 130 C.G.S. electrostatic units, its distance from the rotating disc was .5 cm. When the disc was set rotating the galvanometer indicated a current of from 10^{-4} to 2×10^{-4} ampères. The astatic system,

[1] C. R., 132, p. 1108.

however, remained at rest; though a conduction current of 10^{-4} ampères in a circuit occupying the mean effective position of the charged disc caused a deflection of 15 mm. on a scale 4 meters distant. Cremieu therefore concludes that the electricity carried convectively between the two brushes is without magnetic effect, *i. e.*, that the current in the wire connecting the two brushes is an "open current."

There is, however, a possible explanation of this experiment which requires no such conclusion. As was stated above, the potential of the fixed sector was from 100 to 130 C.G.S. electrostatic units or 30,000 to 39,000 volts, while its distance from the disc was only .5 cm. According to J. J. Thomson (Rec. Res., p. 72) the sparking distance between planes at a difference of potential of 100 C.G.S. electrostatic units is .95 cm. Ebonite is not a perfect insulator, especially for such high potentials. Hence the charge from the fixed sector may have brushed across to the surface of the ebonite facing the disc. This charge would be of opposite sign to that induced on the metallic sectors as they passed under the first brush, and the magnetic effect of that part of the disc between the brushes and nearest the needle would therefore be approximately null.

Present Research.

Method and Apparatus.

The method which has been employed in the present research to put in evidence the existence of the magnetic action of electrical convection is identical in principle with that used by Cremieu in his first experiments, viz., the measurement of the current induced in a coil, on reversing the convection current due to a rotating charged disc.

All experimenters who have worked on this problem have been met by three difficulties, which have required no little patience and considerable experimenting to overcome successfully. These difficulties are: (1) the mechanical jarring caused by the rapidly rotating discs, (2) direct electrostatic effects due to the charged disc, and (3) external magnetic disturbances. The present instance has been no exception to this rule. In the first place, the gal-

vanometer which it was found necessary to employ was so sensitive, that it was impossible to make any observations whatever except between 1:30 and 5 A. M., when the electric cars in the vicinity of the laboratory had ceased making their regular trips.

It is needless to describe the succession of trials which were made to eliminate first one disturbing factor and then another, and the various modifications made from time to time in different parts of the apparatus. I shall describe the apparatus only as it was used in the final quantitative measurements.

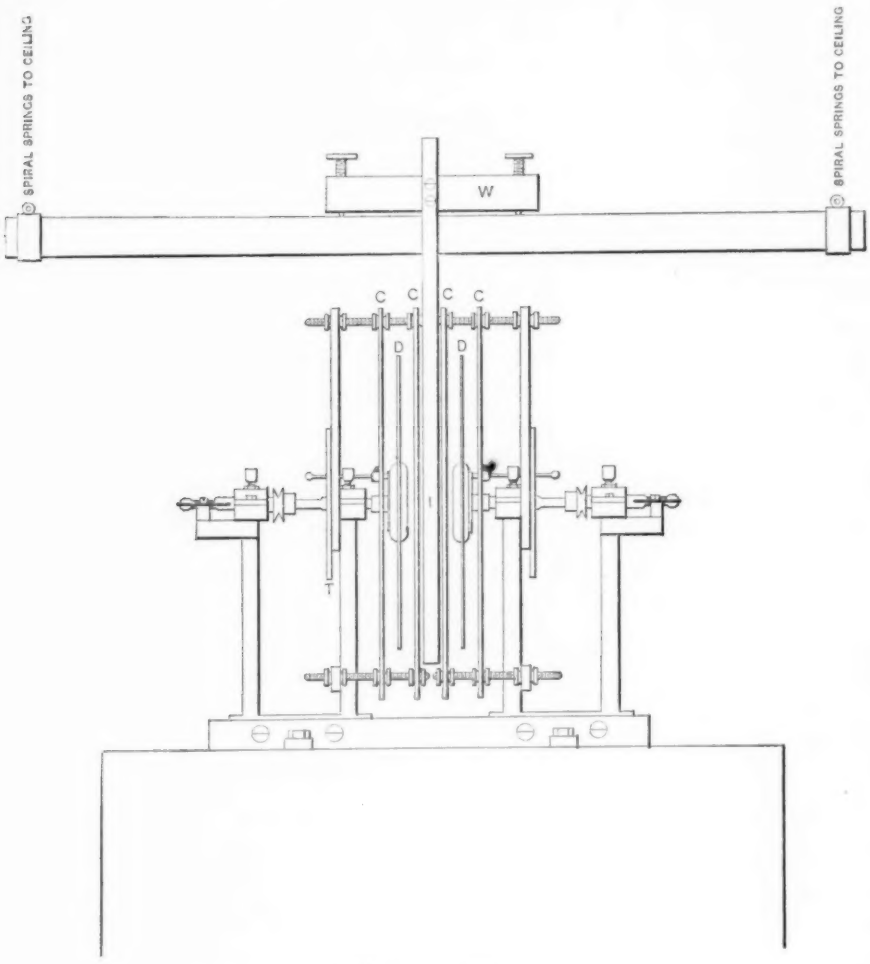
The Disc Apparatus.—This part of the apparatus was constructed several years ago under Professor Rowland's direction, shortly after his experiment in 1889, but had not been previously used. A drawing of it is given in Fig. 1. Two micanite discs *DD*, .336 cm. thick and 30.4 cm. in diameter, gilded on each side, and mounted on ebonite cores, rotate about horizontal axes in the same line. On each side of the discs are condensing plates, formed by rings of tin foil on ebonite plates *cccc* 40 cm. square. The external diameter of these rings is 40 cm., internal diameter 10 cm. By means of adjusting screws it is possible to vary the distance between the discs and condensing plates, and to adjust the latter accurately parallel to the discs. Fixed to the frame of the apparatus is a test coil *T*, through which a conduction current can be sent at will. The frame carrying each disc is fixed separately to base plate of the apparatus, so that the two discs can be placed at any desired distance apart. To each disc is attached a speed counter formed by a cog wheel with 199 teeth gearing directly with a worm on the shaft of the disc.

On the side of the ebonite cores next the frame are fixed brass rings, diameter 6 cm., width 5 cm., making contact with the gilded surfaces by strips of tin foil. Contact is made with these rings by brushes of thin brass mounted on the ebonite plates *cccc*. The brushes nowhere come within 1½ cm. of the frame or the tin-foil condensing plates.

At first ebonite discs were employed, but even though they were 3.5 mm. thick, they soon became so badly warped that their use was extremely unsatisfactory. Besides the excessive jarring produced when they were in rapid rotation, it was impossible to make

accurate measurements of the distance between discs and condensing plates. The micanite discs have served admirably. They are as plane and run as true now as when first put up two months ago.

In the first experiments the discs were charged by points brought up close to their edge. The effect sought could be observed with



⅛ ACTUAL SIZE.

Fig. 1.

this arrangement, but the needle of the galvanometer, when the latter was connected in series with the coil, was exceedingly unstable

when the discs were being charged and discharged, and often even became demagnetized, so that it was frequently necessary to take the galvanometer apart and re-astatize the needle. After weeks of experimenting it was found that this was due to the sparking at the points, unavoidable in this method of charging. On charging by means of the brushes and rings above described, so that there was no sparking at the discs, the spot of light, though it never remained perfectly steady, rarely oscillated over 10 mm.

The Coil.—The constants of the coil, the induced current in which was to be measured, are as follows:

Mean diameter	30 cm.
Width	3.8 cm.
Thickness	1.27 cm.
Number of turns	1295
Resistance	140 ohms
Size of wire	No. 21 B. & S.

This coil I, (Fig. 1) was suspended between the two inside condensing plates, the distance between which was just great enough to allow the coil to hang perfectly free. With regard to this coil, two things were found absolutely necessary; first, to have it completely shielded from all direct electrostatic action, and secondly, to have it so suspended as to be perfectly free from mechanical jarring. The following arrangement, finally adopted after considerable experimenting, proved entirely satisfactory.

Two brass hoops 1.5 cm. thick were placed around the coil, one hoop outside, the other inside. The coil had been previously wrapped with insulating tape. The space between the two hoops was then carefully covered with tin foil. In this way was formed a closed metal case only slightly wider than the thickness of the coil. The terminals of the coil were brought out from this case, and were carefully wrapped in tin foil. The metal case and foil were connected to earth. To the outside hoop were soldered two heavy brass strips fixed to the wooden block *W*, provided with leveling screws. This frame containing the coil was stiffened by a brass rod connecting the strips just above the coil. The block *W* rested on a heavy marble slab suspended from the ceiling by four spiral springs. To prevent the air currents generated by the rapid motion of the disc

from setting this system in vibration, cardboard strips were screwed down over the openings between the condensing plates, so that each disc was completely boxed in.

The Galvanometer.—As has already been stated, the galvanometer employed was an extremely sensitive one. It is an astatic instrument of the ordinary four-coil form, with a low resistance, 58.4 ohms. The needle, which together with its mirror weighs only 2.5 mg., is suspended by an extremely fine quartz fiber, invisible almost in ordinary light. The period of the needle when vibrating in the earth's field was from 3 to 5 seconds, depending on how perfectly the needle was rendered astatic. The period was usually increased to about 25 seconds by cutting down the earth's field by means of control magnets. With this period a current of 1×10^{-10} ampères gives a deflection of 1 mm. on a scale 1.1 meters distant. The deflection of the needle was read by the deflection of the image of an incandescent light filament reflected from the needle mirror, on a ground-glass scale 1.1 meters distant. The needle was absolutely dead beat.

A heavy marble block, resting on a bed of excelsior on a marbel slab bracketed to the wall, formed a support for the galvanometer which rendered it entirely free from mechanical jarring. The galvanometer was also shielded magnetically by three coaxial cylinders of soft iron, closed at the bottom and top by soft iron plates. With this shield on, the needle was fairly steady during the period above mentioned. The accidental deflections of the spot of light with the disc uncharged rarely amounted to over 5 mm. during the time required for a single determination of a deflection—*i. e.*, about one minute, though there was at times a considerable shift of the zero.

The expression "sensibility of the galvanometer" will be frequently used in what follows. By it is meant the deflection in millimeters on the scale 1.1 meters distant from needle, reduced to an infinitesimal arc, produced by a current of 2×10^{-8} ampères flowing through the galvanometer. This value of the current was used simply because it gave a convenient deflection. The scale remained fixed with reference to the galvanometer throughout the experiment. To obtain a constant testing current a Clark cell was con-

nected in series with 101,648 ohms. Around 1,648 ohms of this was a shunt circuit with a resistance of 10,000 ohms. Around 101 ohms of this a second shunt circuit containing the galvanometer was formed, the total resistance of this circuit being 10,000 ohms. This arrangement gives a current of 2×10^{-8} ampères through the galvanometer. A simple mercury key served to throw the galvanometer in or out of this circuit.

The Reverser and Commutator.—The reverser was similar in construction to an ordinary rotary interrupter. Connected to the shaft of the reverser was an eccentric, 1 mm. off center, which operated a commutating device in the circuit between the coil and galvanometer. To the eccentric was attached a lever carrying at one end a small silver rod 1.2 cm. long. When the shaft of the interrupter was turned this rod was given a slight up and down motion between two flat silver springs, between which also was fixed a second silver rod. When the moving rod was at its highest point it made contact with the upper spring, the fixed rod making contact with the lower spring. When the moving rod was at its lowest points, the contacts were reversed. This special form of commutator was found necessary in order to avoid thermal currents. The two rods were connected to the terminals of the coil, the two springs to the galvanometer terminals. The commutator was entirely enclosed in a metal shield connected to earth.

The Charging Apparatus.—The discs were charged by means of a large Voss machine—diameter of revolving plate 50 cm.—and a battery of six gallon Leyden jars. Each pole of the Voss machine was connected to the inside coating of three of the jars. The outside coatings were earthed. It was found convenient to drive the reverser at a speed of from 3 to 5 revolutions per second, which reversed the charge on the discs 12 to 20 times a second. As the discs and condensing plates formed a condenser of considerable capacity, it was therefore found necessary, in order to keep up the potential of the battery, to keep the Voss machine running at a considerable speed, in fact, as fast as the construction of the machine permitted. This was accomplished by means of a small electric motor, the speed of which remained admirably constant. When the discs were being charged, the potential seldom varied over 3 per cent.

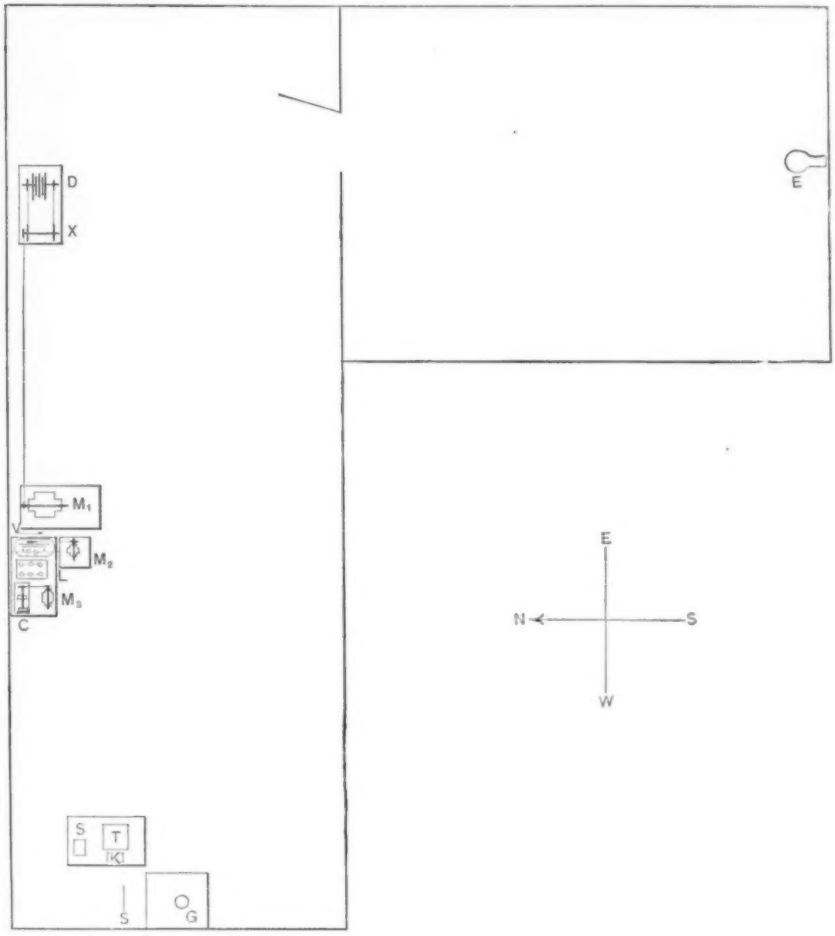
General Arrangement of the Apparatus.—This is shown in Fig. 2. The letters indicate the following :

E an absolute electrometer.
D disc apparatus and coil.
M_1 motor driving discs.
M_2 motor driving Voss machine.
M_3 motor driving commutator.
V Voss machine.
L Leyden jars.
C commutator.
S a high potential reversing switch.
K key in galvanometer circuit.
T resistance boxes and cell forming test circuit.
G galvanometer.
s scale of same.
X counter shaft.

The advantage of this galvanometer method of detecting the existence of the magnetic action of electrical convection over the magnetometer methods is clearly seen in this possible arrangement. Instead of having the delicate magnetic detector which must be employed, up close to the rotating discs, where it is subject to all kinds of disturbing elements, as is necessary when a magnetometer is used, it can in this method be placed as far as one may desire from all the rest of the apparatus. The three motors M_1, M_2, M_3 were so placed as to reduce their action on the coil and galvanometer to a minimum. When placed as shown there was no appreciable action on the coil, but on turning the current on the large motor M_1, the zero of the galvanometer was changed about 15 mm. As the speed of the motor was kept constant, however, during a series of observations, this was a perfectly steady deflection, and consequently of no particular disadvantage. The discs were set up at right angles to the meridian, for convenience in placing the rest of the apparatus. There was no appreciable effect due to their thus cutting the lines of force of the earth's field, *i. e.*, there was no effect on running the apparatus with the discs uncharged.

In the figure all connections are omitted for the sake of clearness. These, however, can be readily described.

Galvanometer Circuit.—This circuit was completely enclosed in a continuous metal shield throughout its entire extent. This shield was connected to earth. The lead wires from the galvanometer



12′ TO THE FOOT.

Fig. 2.

lead first to a specially constructed mercury switch *K*, enclosed in a wooden box, lined with tin foil—the switch was thus protected both from thermal and from electrostatic effects. One of the leads was connected to the earth. From the switch ran two lead wires to the springs of the commutator. The rods of the commutator were connected to the terminals of the coil.

Charging Connections.—All high potential wires were suspended by silk threads. From the two poles of the Voss machine ran two wires to two terminals of the reversing switch S. From the other two terminals ran two wires to the reverser. The brushes of the reverser could be arranged so that at any instant the two discs could be charged either alike or oppositely, as desired.

If the discs are set rotating in the same direction, the commutator and Voss machine also set rotating so as to charge the discs at any instant with the same sign, then on throwing the galvanometer in series with the coil, the spot of light on the galvanometer scale should move off a distance D from its position on open circuit. If the order of charging with respect to the commutation is reversed, as can be done by reversing the high potential switch S, then the spot of light should move off a distance D on the other side of its position on open circuit. Hence, on reversing the high potential switch S, keeping everything else unchanged, the spot of light should change its position by an amount $2D$. This was the deflection always observed. This deflection varied from 30 to 80 mm., depending upon the conditions. Its direction always reversed with the direction of rotation of the discs, and was always such as should be expected from Ampère's rule. This latter was determined by comparison with the deflection produced by a conduction current, reversed in the same manner as the charge on the discs, flowing in the test coil T on the disc apparatus.

At times a deflection was noticed on reversing the switch S with the discs at rest, but the other parts of the apparatus running. This, however, was invariably traced to the temporary failure of the insulation either of the ebonite cores of the disc or of the ebonite between the brushes and the tin foil condensing plates, due to the surfaces becoming greasy. By cleaning the surfaces with benzine and then with alcohol, this deflection was always completely suppressed. The insulation was usually thus cleaned at once every night, and frequently oftener. *No readings were ever taken when there was any perceptible deflection with the discs at rest.*

Calculation of the Effect.

The strength of the convection current produced by the rotation of an elementary annular surface of radius r and width dr, carrying a charge of surface density σ is

$$dI = 2\pi r dr \frac{N\sigma}{v}$$

where N is the number of revolutions per second and v the ratio of the two systems of electrical units. The quantity induced in the coil I (Fig. 1) connected with the galvanometer by reversing this, *i. e.*, by reversing the sign of σ is

$$dq = 4\pi r dr \frac{N\sigma}{v} \times \frac{M'}{R}$$

where M' is the coefficient of mutual induction of the ring and the coil I, and R the total resistance of the circuit consisting of coil and galvanometer. Let the charge σ be reversed C times a second and the induced current be commutated as above described. The value of the rectified induced current will be

$$4\pi r dr \frac{N\sigma}{v} \frac{M'}{R} C$$

and the steady deflection of the spot of light from its equilibrium position will be

$$dD = 4\pi r dr \frac{N\sigma}{v} M'K$$

where K is a factor depending on the resistance of the circuit, the number of reversals per second, and the sensibility of the galvanometer, or $2M'K$ is the deflection given by a unit current reversed in the ring C times a second under the same conditions. Hence the total deflection due to one surface of the disc is

$$D_1 = \frac{4\pi NK}{v} \int_{R_1}^{R_2} \sigma r M' dr.$$

Since there are four surfaces the entire effect due to them all can be written

$$D = 4D_1 = \frac{16\pi NR}{v} \int_{R_1}^{R_2} \sigma r M dr$$

where M is the mean value of M' for the four surfaces.

Considering D the observed deflection, we have

$$v = \frac{16\pi NK}{D}\int_{R_1}^{R_2} \sigma r M dr.$$

The value of v thus determined is a test for the accuracy of the assumption that a convection current is magnetically equivalent to a conduction current.

The surface density of the discs is uniform except on the edge and at the center opposite the opening in the tin-foil condensing plates. The uniform surface density over the main body of the disc is

$$\sigma = \frac{V}{2\pi(B - \beta)}$$

where V is the potential of the disc, the condensing plates being earthed, B the distance between the condensing plates, and β the thickness of the disc.

The excess on the edge of each side is (Max. Elec. and Mag. § 196)

$$q = 2\pi R_1 \sigma \frac{B}{\pi} \log_e \left(2 \cos \frac{\pi\beta}{2B}\right)$$

$$= \frac{VR_1 B}{\pi(B - \beta)} \log_e \left(2 \cos \frac{\pi\beta}{2B}\right)$$

The effect of this excess can be calculated by considering it as concentrated in a circle of slightly smaller radius R' than that of the disc. The lack of uniformity opposite the internal edge of the condensing plates may be allowed for by taking for R_1 a value somewhat less than the radius of the opening in the tin foil, and considering the surface density uniform. This last correction is less than one per cent., since the velocity of this portion of the disc is very small and its effect on the coil also very slight. We then have

$$v = \frac{4vNK}{(B - \beta)D}\left[\int_{R_1}^{R_2} rMdr + \frac{R_1 B}{\pi} \log_e \left(2 \cos \frac{\pi\beta}{2B}\right) M_R\right].$$

M and $\int Mrdr$ can be calculated from the dimensions of the apparatus by means of elliptic integrals, provided the coil I is perfectly

uniform. However, there were considerable variations in the dimensions of the coil from point to point, so that this method was not deemed sufficiently accurate. Hence the following scheme, which amounts practically to an experimental determination of M and a graphical calculation of $\int Mdr$ was adopted. Twelve concentric coils of one turn each were mounted on a plane board. This board could be clamped in turn up against each surface of each disc. The radii of the coils varied from 4.3 to 16.0 cm. All leads were carefully twisted. Connections with a storage battery, 110 volts, were so arranged that a current of $\frac{3}{4}$ of an ampère could be sent at will through the reverser and any one of the coils on the disc, and the current induced in the coil I on running the reverser measured. Instead of employing for this purpose the sensitive galvanometer above described, an ordinary D'Arsonval about 1,000 times less sensitive was used. Hence the large value of the inducing current. The D'Arsonval could be used during the day; also its readings were much more reliable than those of the astatic instrument. The "calibration of the disc apparatus" then consisted in sending a given current through the test coil T with the reverser running, and noting the deflection of the D'Arsonval connected in series with the coil I. The same current was then sent through coil No. 1 on the disc, the deflection noted; then again through coil T, the deflection noted, and so on for each of the twelve coils when clamped up in turn against each face of each disc. The deflection due to the coil T was determined before and after every determination for a coil on the disc, in order to eliminate any error due to the variation in speed of the commutator. The ratio ρ of the deflection due to the given current in each coil to the deflection due to the same current in coil T_1 was determined from these readings. To find the value of the factor $2MK$ it is then necessary to know only the deflection of the astatic galvanometer produced by a unit current in coil T with the reverser running. Call this J. Then $2MK = J\rho$. (This of course depends on the sensibility of the galvanometer and the number of reversals per second—see below.) It is hardly necessary to state that the relative positions of the discs, coil I, and coil T, remained fixed throughout the experiment.

It was found that the values of ρ for any one coil in corresponding positions on the two discs were very nearly the same, within about one per cent., thus showing that the two sides of the apparatus were very nearly symmetrical with respect to the coil. The values for the two sides of the same disc differ about 5 per cent. The mean of the ratio for the four positions of each coil was then plotted as ordinates to the radii of the coils as abscissæ. The curve thus found represents $\frac{2KM}{\Delta}$. Multiplying the ordinate of each point by its abscissæ, we get a curve representing $\frac{2KMr}{\Delta}$. The area of this from R_1 to R_2 is

$$\frac{2K}{\Delta}\int_{R_1}^{R_2} Mrdr.$$

Call this μ. The value of $\frac{2KR_1}{\Delta} M_{R'}$ is also given from the first curve. Call this ν.

Then

$$v = \frac{4\pi N\Delta}{(B-\beta)D}\left[\mu + \frac{\nu B}{\pi}\log_e\left(2\cos\frac{\pi\beta}{2B}\right)\right]$$

Two independent "calibrations" of the disc apparatus were thus made, the first after set 7, the second after set 17. Table I. gives the radii of the coils, the corresponding values of ρ for each calibration, and the mean of the two sets.

TABLE I.

Radii.	ρ_1	ρ_2	Mean ρ	Radii.	ρ_1	ρ_2	Mean ρ
4.39	.146	.143	.145	12.00	1.293	1.294	1.294
5.98	.284		.284	12.82	1.522	1.501	1.512
7.87	.505	.504	.505	13.57	1.692	1.697	1.695
9.04	.678	.682	.680	14.34	1.880	1.885	1.883
10.02	.845	.848	.847	15.21	2.036	2.065	2.051
11.05	1.071	1.070	1.071	15.96	2.159	2.162	2.161

The factor Δ is equal to the deflection of the galvanometer due to the current, commutated, induced in the coil I on reversing a unit current in the coil T, as above described. This quantity therefore depends on the number of reversals of the current per second, and

the sensibility of the galvanometer. The first idea which suggested itself was to arrange a test circuit so that the deflection produced by a given current thus reversed in the test coil T could be determined alternately with the deflection produced by reversing the charge on the rotating discs, keeping the speed of the reverser and the sensibility of the galvanometer unchanged. This, however, was not practicable. In order to insure a steady contact between the brushes and the brass sectors of the reverser, it was necessary that the brushes bear with some little pressure on these sectors. With the brushes thus adjusted, however, the particles of brass gradually rubbed off soon formed a thin metallic bridge across the intervening ebonite sectors, thus destroying the insulation for high potentials. When the reverser was therefore being used to reverse the charge on the discs, it was necessary to have the brushes so adjusted that they barely touched the brass, in which case the contact for the test current was destroyed. Moreover, when the brushes were adjusted first one way and then another, the speed of course changed. Hence another method of procedure was adopted.

By a series of preliminary experiments it was found that, on reversing a given current in the coil T, as above described, the factor J was directly proportional to the sensibility of the galvanometer and to the number of reversals per second, at least within the limits used—8 to 20 reversals per second. Consequently, instead of determining J directly for each set of readings, the sensibility of the galvanometer S, and the number of reversals per second C, were determined instead. Writing

$$J = ASC$$

the above formula for v becomes

$$v = \frac{4\pi NASC}{(B - \beta)D}\left[\mu + \frac{\nu B}{\pi}\log_e\left(2\cos\frac{\pi\beta}{2B}\right)\right].$$

The factor A was determined from time to time throughout the experiment as follows. The sensibility of the galvanometer S was first determined. The brushes were then properly adjusted, a known current i sent through the coil and reverser, and the reverser and commutator set running. The deflection due to the

current induced in I by this current i in T was then determined; also the number of reversals per second C. The double deflection $2D$ was the quantity measured directly. We have the formula

$$A = \frac{D}{SCi}$$

The current i was obtained from an ordinary commercial cell in series with several thousand ohms. The e.m.f. of this cell was determined by comparison with a standard Clark cell. The total resistance of the circuit was measured by a standard bridge. The internal resistance of the battery was less than an ohm. In some determinations a Daniell cell was used in place of the commercial cell. Table II. gives a series on determinations of A, for various values of the quantities involved. i is given in C.G.S. electromagnetic units. The value of A is seen to be constant within the limits of error of observation. After using the commutator for these determinations it was always necessary to thoroughly clean the reverser with emery cloth and to reset the brushes, before it could again be used to reverse the charge on the discs.

TABLE II.

S	$2D$	C	i	A
153	158	7.46	$.628 \times 10^{-4}$	$.1101 \times 10^{4}$
205	107	7.34	.317	.1122
197	200	14.7	.317	.1089
172	176	14.2	.317	.1136
177	158	12.8	.317	.1100
171	318	13.4	.632	.1098
214	245	16.8	.314	.1085
86.7	88.2	16.5	.276	.1117
160	198	20.3	.276	.1105
215	217	16.8	.276	.1089
				Mean : .1104

The quantities to be measured in conjunction with the deflection due to the rapid reversal of the charge on the rotating discs are the following :

1. The number of reversals per second. This was determined by a velocimeter attached to the shaft of the commutator. The

time required for 200 revolutions was determined by a stop-watch. One turn of the shaft corresponds to four reversals.

2. The speeds of the two discs. The time required for 20 complete turns of each of the speed counters was determined by a stop-watch. Each counter has 199 teeth, so that this corresponds to 39,800 turns of the disc. The speeds of the two discs agreed very well. The average speed of the two is the quantity recorded below under N.

3. The sensibility of the galvanometer. This was determined as already described.

4. The difference of potential between the discs and the condensing plates; the condensing plates were always earthed. This was determined by means of an absolute guard ring electrometer, the same instrument as that used by Rowland and Hutchinson in 1889. The disc attached to the balance arm and its guard ring were earthed. The lower plate was connected to the discs through the reverser. By a simple device it was so arranged that this connection was made only when the discs were charged in one way, positively, say, so that the disc of the electrometer did not fluctuate up and down as it would have done had the lower plate been connected permanently to the rotating disc. Had the lower plate connected directly to a pole of the Voss machine, the potential measured would have been higher than that of the discs, since in the interval during which the discs were disconnected from this pole, its potential would rise, due to the storing of the charge in the Leyden jars, for the Voss machine was kept rapidly rotating all the time. The potential then measured by the electromoter was that to which the discs were brought when charged positively, say. By reversing the switch S, the potential to which they were brought when charged negatively was similarly determined. The mean of the positive and negative values of the potential thus determined is the quantity recorded below under V.

The difference of potential between the two plates of the electrometer is

$$V = \delta \sqrt{\frac{8\pi g M}{A}}.$$

In this laboratory $g = 980.1$. A, the area of the disc, corrected for

the annular space between it and its guard ring, is 80.11. Hence $V = 17.56\, \delta \sqrt{M}$. δ is the distance apart of the plates, read from a scale attached to the lower plate. M is the mass on the scale pan; δ and M are the quantities determined for each measurement.

A series of measurements was then made as follows. First one observer determined the sensibility of the galvanometer. The zero was noted, the test current 2×10^{-8} ampères sent through, a reading made, the connection broken, and a zero again noted. This was usually done three times, and the mean deflection taken as the sensibility. The commutator and Voss machine were then started, and a test made to see that there was no effect when the discs were at rest. The discs were then set in rotation, and when they had reached a constant speed, a second observer noted the speed of each, and also that of the commutator, while the first observer measured the potential of the discs, with the switch S first thrown north, and then south. The deflection produced by the convection current was then determined by the first observer as follows: With the switch S thrown north, the galvanometer was thrown in circuit, and a reading taken. The switch was then thrown south, a second reading taken, then north again, and a third reading taken. The difference between the second and the mean of the first and third readings was taken as the value of $2D$. The switch was then thrown south, then north, then south, a reading taken each time. Again the difference between the second and the mean of the first and third was taken. In this way variations in the zero were largely eliminated. The above operation was repeated twice. The speeds and potentials were then determined, a similar set of readings taken, and the speeds and potentials once more determined. This usually required the greater part of one of the forty-minute periods during which the galvanometer could be used. During the next period the direction of rotation of the discs was reversed, and a similar set of readings made. It is hardly necessary to state that with apparatus as complicated as that used, accidents were frequent, and often a whole night was spent without obtaining a satisfactory set of readings.

There are two ways of employing the disc apparatus to put in evidence the effect sought. The two discs may be rotated in the

same direction, and, at any instant, charged alike; or, they may be rotated in opposite directions, and, at any instant, charged oppositely. Both methods have been employed, but the majority of readings were taken with the discs charged oppositely and rotating in opposite directions, as the needle of the galvanometer was much more steady under these conditions.

Table III. gives an example of a complete set of readings, taken under these latter conditions. The first four columns give the readings for the sensibility, the next three the readings for the potentials, the next eight the readings for the deflection, and the last three the speeds. S is the sensibility of the galvanometer; M the mass on the scale pan of the electrometer; δ and δ' the distance apart of the electrometer plates, less .26 cm. the zero correction of the scale of the electrometer, when the discs are charged positively and negatively respectively; N and S indicate the position of the handle of the reversing switch; C' is the time required for 200 turns of the commutator shaft, N_1 and N_2 the time required for 20 complete turns of the speed counters on the two discs.

This table is a fair example of the general run of readings. The large variations in the separate determinations of $2D$ are due to the fact that the spot of light was always unsteady when the charge on the discs was being rapidly reversed, oscillating over from 10 to 15 millimeters. This unsteadiness was probably due to the fact that the metal case enclosing the coil is not a complete shield against rapidly varying charges. It will also be noticed that at times there was a change of the zero. This was due to variations in the field at the galvanometer due to outside causes.

In Table IV. are given the mean values of the various factors of a number of sets of determinations, taken between the middle of March and the first of May; also the value of v calculated for each set in the manner above described. Observations were attempted only on those nights when the atmosphere was comparatively dry. A bracket in the following table indicates that the sets included under it were taken immediately following one another on the same night.

In connection with sets 14 and 15 a further series of readings was made, which may be looked upon as an additional proof of the ex-

Table III.

March 27, 1901. *Rotation: I—, II+.*

Zero.	Read.	Zero.	S	M	δ	δ'	N	S	N	S	N	S	$2D$	$2D$	C	N_1	N_2
69	283	66	215	.25	.65	.98	177	93	170	105	142	70	81	54	65.1	38.3	38.6
66	282	60	219				115	67	117	66	126	64	49	61			
60	279	63	217		.66	1.01	118	73	109	55	117	62	41	58			
							97	23	93	75	110	42	72	51	64.8	39.0	40.2
							125	62	120	58	120	70	61	56			
					.68	1.00	105	65	118	68	119	75	47	47	62.8	38.0	39.8
			217		.66	1.00							Mean	56.5	64.2	38.5	39.5
			Cor. 214		.83								Cor.	56.5		39.0	
					.26												
					1.09									Hence			
					Hence $V = 9.55$									$C = 12.5$			
					$v = 3.16 \times 10^{10}$									$N = 102.1$			
31	241	29	211	.25	.94	1.15	55	145	65	150	68	147	85	81	61.2	38.2	39.0
29	243	31	213				55	155	65	149	68	138	95	76			
30	245	28	216		.86	1.09	67	150	68	144	58	148	82	88			
							50	115	40	132	65	115	70	59	7.7	38.6	39.6
							45	132	48	130	52	118	85	72			
					.92	1.12	55	120	52	124	55	121	66	77	59.0	38.0	39.8
			213		.91	1.12							Mean	78.0	59.3	38.3	39.5
			Cor. 210		1.015								Cor.	77.8		38.9	
					.26												
					1.275									Hence			
					Hence $V = 11.20$									$C = 13.5$			
					$v = 2.84 \times 10^{10}$									$N = 102.3$			

TABLE IV.

No.	*B*	*I*	*II*	*S*	*V*	*C*	*N*	$2D$	v
1	2.08	+	—	240	10.52	10.8	99.0	65.3	2.84×10^{10}
2	"	—	+	240	10.10	10.9	99.4	58.7	3.05
3	"	—	+	192	8.51	12.1	90.6	42.2	2.90
4	"	—	+	214	9.55	12.5	102.1	56.5	3.16
5	"	+	—	210	11.20	13.5	102.3	77.8	2.84
6	"	+	—	202	9.81	13.2	99.1	63.3	2.82
7	"	—	—	174	9.30	11.7	83.5	36.3	2.97
8	2.047	—	+	189	10.35	15.4	97.6	63.7	3.19
9	"	+	—	189	10.83	15.0	77.6	53.2	3.09
10	"	—	—	171	9.30	13.4	89.9	41.0	3.24
11	"	+	+	165	11.40	19.8	86.5	69.1	3.23
12	2.394	—	+	88	10.41	19.1	83.2	29.2	2.93
13	"	+	—	99	10.12	17.6	89.7	33.8	2.75
14	"	+	—	195	9.56	22.0	75.6	63.7	2.83
15	"	—	+	193	9.90	21.2	82.3	68.3	2.87
16	"	—	—	190	9.96	20.6	87.9	66.2	3.00
17	"	+	+	201	10.31	20.8	78.3	62.0	3.17

Mean: 3.05×10^{10}

istence of the effect sought. The discs were charged oppositely throughout. First was taken a complete set of readings on reversing the switch *S* while the discs were at rest, the remainder of the apparatus running as usual. The discs were then set rotating, both positively, and a second series of readings taken; then one of the belts from the counter shaft to the disc was crossed so that I. rotated +, and II. —, and a third series taken; then the main belt from the motor was crossed so that I. rotated — and II. +, a fourth series taken; finally, the belt from counter shaft to disc was put straight again, so that both discs rotated negatively, and a fifth series taken. In connection with sets 16 and 17 a similar series of readings was made, except that here both discs were charged alike. Here are the observed and calculated values for the deflection for the various cases.

In all of the preceding the surfaces both of the discs and of the condensing plates were uniform. A series of experiments early in the winter had shown that the qualitative effect was the same under these conditions as when the surfaces of the discs were divided into a number of separate sectors, and charged at the periphery by a

TABLE V.

Speeds.		Charged.		Deflection.	
I	*II*	*I*	*II*	Obs.	Cal.
0	0	±	∓	+ .9	0.0
+83.2	−88.9	±	∓	+ 2.0	+ 2.1
−78.4	−73.4	±	∓	−63.7	−60.1
−79.3	−74.2	±	∓	+ 2.3	+ 2.1
−83.0	+81.9	±	∓	+68.2	+65.0
0	0	±	±	+ .1	0.0
−86.9	−88.8	±	±	−66.2	−68.2
+88.0	−89.6	±	±	− 1.0	− .4
−88.0	+89.6	±	±	+ 2.0	+ .4
−78.3	+78.3	±	±	+62.0	+66.0

point. To see if the quantitative effect was also the same, the following experiment was performed. The conducting surfaces of both the discs and the condensing plates were each divided into six sectors by radial scratches .75 mm. wide. The internal edges of the condensing plates were connected by a ring of tin foil 1 mm. wide. The sectors of the discs were connected only by the charging rings on the ebonite cores. If then the effect observed was in any way due to conduction currents in the metal surfaces, this arrangement should certainly greatly alter its magnitude. Observation, however, showed that this was by no means the case. In Table VI. are given the results of four series of measurements. The values of v calculated from these lie well within the range of accuracy of the experiment.

TABLE VI.

No.	*B*	*I*	*II*	*S*	*V*	*C*	*N*	$2D$	v
18	23.94	+	—	159	11.99	16.9	90.0	58.7	2.89
19	"	—	+	218	13.60	17.1	81.4	82.0	2.96
20	"	+	+	218	12.45	17.2	76.9	76.7	2.75
21	"	—	—	195	14.00	15.3	106.3	80.3	3.23
								Mean :	2.96

The above results, therefore, show beyond any doubt that *electric convection does produce magnetic action*, or, more exactly, that, within the errors of observation, the current induced in a coil by

reversing a convection current in its vicinity, is equal to the current induced in this coil by reversing a conduction current of the same strength as the convection current in a circuit coinciding with the path of the convection current.

The conditions of the experiment above described are still capable of considerable improvement. A number of alterations are to be made next winter, and it is hoped that much more consistent results will then be obtained. Cremieu's recent experiments will also be repeated, with the view of seeing if the explanations above offered will bear experimental test. There also remain a number of questions in regard to the effect of moving electrified bodies still unanswered, at least satisfactorily; for example, the motion of a dielectric in a uniform field; also the reverse of the above experiment. These problems are also to be attacked.

It is a source of great satisfaction to me that the above investigation was practically completed before the death of Professor Rowland. His advice and criticism throughout the work were invaluable.

To Professor Ames also I am indebted for much valuable advice. I also take this opportunity of thanking Mr. N. E. Gilbert for his valuable assistance in the early part of the work, and Messrs. J. T. Barrett and Jas. Barnes for their help in taking the final readings.

EFFECT OF DRAWING ON THE ELASTICITY OF COPPER WIRE.

BY J. R. BENTON.

WHEN different specimens of the same substance are used for determining elastic moduli, the results vary considerably, so that the values obtained for any one specimen describe the behavior of that specimen only, and do not hold universally for the substance in question. This discordance is explained by the assumption of differences in the physical condition of the various specimens. Such differences are produced in the case of metals by rolling, hammering or drawing, or by varying the manner of cooling from high temeratures.

Determinations of the elastic moduli of metals are most often made on wires. It is therefore especially important to know how the elasticity of wires is affected by the processes used in their manufacture; of these, drawing is the most important.

This article describes some experiments on the changes in elasticity which the process of drawing produces in copper wires. I shall first give a statement of the results obtained from the experiments, and leave till afterwards the discussion of the methods of observation, as they will be of less interest to the general reader.

STATEMENT OF RESULTS.

The following are the principal facts that have come to light in the experiments:

1. If a copper wire is first annealed by heating electrically[1] to redness and is then drawn, its modulus of rigidity decreases, and Young's modulus increases.[2]

[1] It has been shown that the passage of an electric current through copper wire does not influence Young's modulus, excepting in so far as it heats the wire. It is probably safe to assume further that the current has no specific effect on the modulus of rigidity. See M. C. Noyes, PHYS. REV., 3, 432–447, 1896.

[2] The increase of Young's modulus in drawing copper wire was observed by Wertheim, Compt. rendus, T. XV., p. 110; Pogg. Ann. Ergänzungsband, II., pp. 1–70.

2. Each successive drawing causes a further diminution of the modulus of rigidity, and a further increase of Young's modulus; for both moduli the amount of change becomes less with each drawing.

3. If finally the wire is annealed after having been drawn several times, the modulus of rigidity returns to a value considerably greater than its original value, and Young's modulus to one considerably less than its original value.

The numerical results for two pieces of wire taken from the same coil are given in Table I.

TABLE I.

Treatment of Wire.	Modulus of Rigidity in Dynes per sq. cm.	Young's Modulus in Dynes per sq. cm.	Diameter in cms.
Annealed and drawn once.	$10^{11}\times$ (Wire A.) 4.017 ± 0.010	$10^{11}\times$	0.15042
Drawn 2 times. . . .	3.946 ± 0.013		0.13914
" 3 " . . .	3.919 ± 0.011	13.87 ± 0.14	0.13060
" 6 " . . .	3.876 ± 0.011	13.90 ± 0.13	0.11220
" 9 " . . .	3.863 ± 0.008	14.20 ± 0.12	0.09410
Annealed again . . .	4.322 ± 0.008	11.90 ± 0.12	0.09318
	$10''\times$ (Wire B.)	$10''\times$	
Annealed.	4.177 ± 0.012	12.82 ± 0.14	0.16174
Drawn once. . . .	4.015 ± 0.011	13.21 ± 0.14	0.15082
Drawn 3 times .	3.961 ± 0.010	12.90 ± 0.13	0.13662
" 5 " . .	3.948 ± 0.008	13.26 ± 0.13	0.12298
" 7 " . . .	3.945 ± 0.008	13.40 ± 0.12	0.11238
" 9 " . .	3.897 ± 0.008	13.32 ± 0.12	0.10012
Annealed again . . .	4.305 ± 0.008	11.09 ± 0.12	0.09856

The values given for Young's modulus hold for isothermal extension, while those given for the modulus of rigidity hold for adiabatic torsion.

The results are shown graphically in Figs. 1, 2, 3 and 4. The vertical line through each plotted point in the diagrams gives the limits of probable error for the corresponding determination.

It is probable that the difference in elastic properties between the wires annealed before drawing and those annealed after drawing is due to the fact that the latter cooled from red heat more rapidly on account of their smaller diameter, and were therefore more completely annealed.

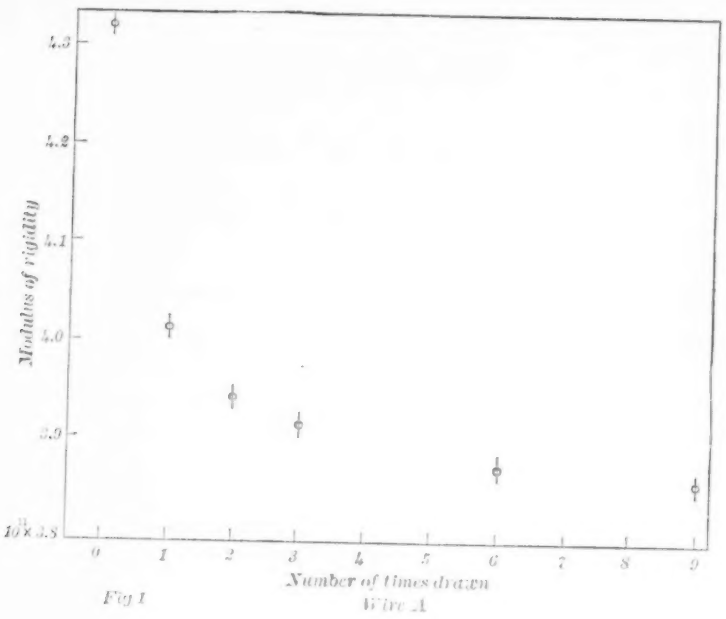

4.3
4.2
4.1
4.0
3.9
$10^{11} \times 3.8$
Modulus of rigidity
0 1 2 3 4 5 6 7 8 9
Number of times drawn
Wire A
Fig 1

Fig. 1.

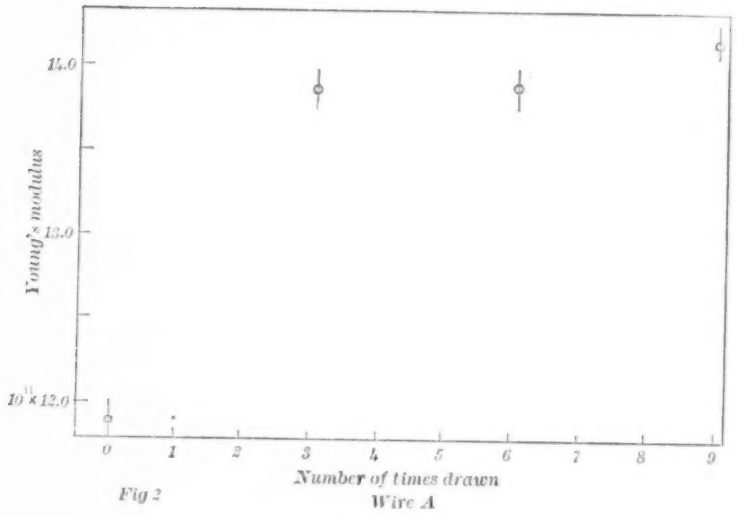

14.0
13.0
$10^{11} \times 12.0$
Young's modulus
0 1 2 3 4 5 6 7 8 9
Number of times drawn
Wire A
Fig 2

Fig. 2.

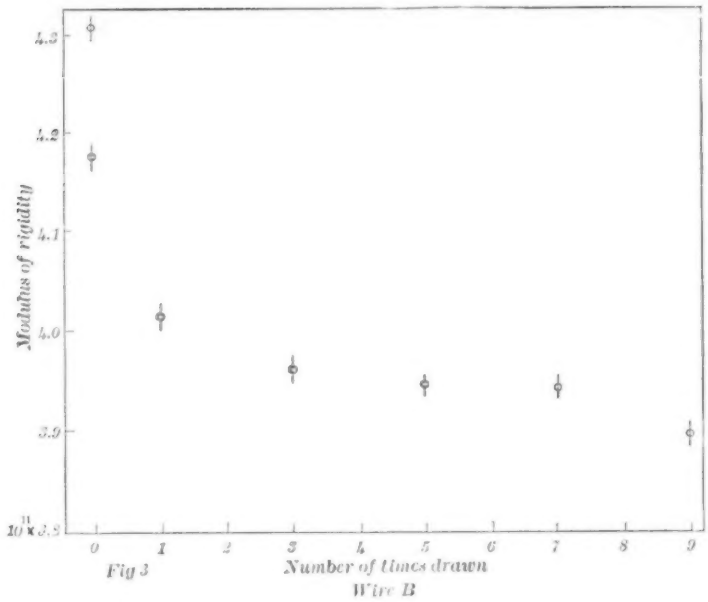


Fig 3

Fig. 3.

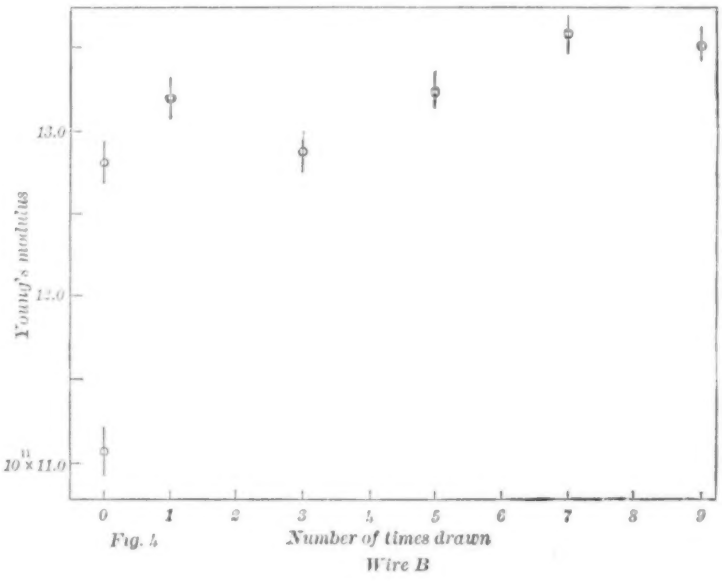


Fig. 4.

Fig. 4.

It is a matter of common observation that drawn copper wires offer much greater resistance to bending than annealed ones. This would be explained by an increase in Young's modulus. But the change in Young's modulus, as seen in Table I., is not sufficiently great to account for the very considerable increase in resistance to bending. We have no right, however, to assume that the change in Young's modulus is uniformly distributed over the cross-section of the wire. If, for example, it should happen that the modulus increased for the outer part of the cross-section, but decreased for the inner part, we might have no difference in the elasticity of extension, but would nevertheless have an increase in the elasticity of bending.

These considerations seemed to make it worth while to determine Young's modulus for the same wires by the method of bending. The results are given in Table II. Contrary to expectation the values obtained by flexure were considerably less than those obtained by extension. This would seem to ndicate (though it would by no means prove) that Young's modulus increases more in the interior of the wires than near the surface. It is to be noticed that the values obtained by the two methods very nearly agree for the annealed wire. The greater stiffness of drawn wires as compared with annealed wires must then be due simply to the increase in the *limit* of elasticity. The flexural elasticity itself increases only slightly in drawing.

TABLE II.

Young's modulus determined by bending. (*Wire B.*)

Treatment of Wire.	Young's Modulus in Dynes per sq. cm.
Annealed and drawn once.	$10^{11} \times 11.23 \pm 0.12$
Drawn 3 times.	11.79 ± 0.12
" 5 "	11.88 ± 0.12
" 7 "	11.83 ± 0.12
" 9 "	12.08 ± 0.12
Annealed again.	10.82 ± 0.12

DETERMINATION OF THE MODULUS OF RIGIDITY.

In determining the modulus of rigidity the following method was used: A wire (a) about 235 cm. long was fastened at the top

to a firm bracket (b), the end of the wire being tightly clamped between steel plates. On the lower end of the wire was clamped a rod (c), the ends of which were fastened so as to prevent torsion of the lower end of the wire. At the middle of the rod was a hook, from which weights (d) could be suspended so as to make the wire hang straight. Exactly half way between b and c a brass disk (e), 15 cm. in diameter, and weighing about 1 kg., was fastened. On the brass disk two lead cylinders (f, f) (4.7 cm. in diameter; 2.5 cm. in height) could be laid. These cylinders were always laid in exactly the same position; this was attained by means of small pegs (g) which projected from the disk e, each cylinder being brought into contact with the proper pegs.

Fig. 5.

The method of observation was as follows: the period of torsional vibration was determined when the lead cylinders were in place; then the lead cylinders were replaced by hollow brass cylinders of the same dimensions externally, and the period was again determined. The purpose of the brass cylinders was simply to insure that the resistance of the air to the motion of the disk should be the same for both determinations. The period of swing in the two cases, and the difference in the moment of inertia, together with the dimensions of the wire, give the necessary data for determining the modulus of rigidity.

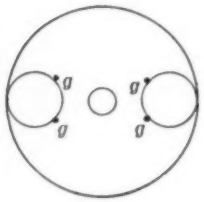


Fig. 6.

The modulus of rigidity F can be calculated from the formula

$$F = \frac{4\pi l' K}{r^4(t_2^2 - t_1^2)}, \qquad (1)$$

where l' is the length between the disk and either end of the wire, K is the difference in moment of inertia due to substituting the lead cylinders for the brass ones, r is the radius of the wire, and t_2, t_1, are the periods with the lead cylinders and the brass cylinders, respectively. If we put $\sqrt{\frac{m}{\pi l \sigma}}$ in place of r, where m is the mass of

wire, l is its total length, and σ its density, the formula becomes

$$F = \frac{4\pi^3 l^2 \sigma^2 K l'}{m^2(t_2^2 - t_1^2)}. \qquad (2)$$

Of the quantities in this formula, l and l' were determined by direct measurement with a meter scale; their errors were taken as not greater than 0.2 cm., and 0.1 cm. respectively, or about 0.1 % in each case. σ was determined by weighing the wire in air and in water. One determination was made for each wire experimented on, and the mean was used, being 8.849 for the annealed wires, and 8.840 for the drawn wires, the probable error being in each case $\pm$ 0.005, or about 0.06 %. If any change in density took place after the first drawing of the wire, it was within the limit of the experimental errors.[1] K was calculated from the dimensions and masses of the two lead cylinders and the two brass cylinders. Its value in C.G.S. units was 21210 with a probable error not greater than 17, or about 0.08 %. m was determined by weighing the wire; its probable error was taken as not greater than 0.0003 gr., or about 0.001 %. t_1 and t_2 were determined by observing the time when a mark on the disk swang past its position of rest at every fifth swing for about 250 swings; by properly combining these observations the period of the disk could be determined with a probable error of 0.0006 sec., or 0.01 % to 0.03 %. This gives for $(t_2^2 - t_1^2)$ a probable error not greater than 0.1 %. In determining the period an ordinary watch was used, with which it was possible, after practice, to read to the nearest fifth of a second. The combination of these errors gives the probable error of F between 0.2 % and 0.4 %.

The formula used assumes (1) constancy of external conditions, (2) homogeneity of the wire, (3) perfect firmness of the supports, and (4) that the wire has the shape of a circular cylinder. The possible imperfect fulfillment of these assumptions leads to the consideration of the following possibilities of systematic error:

[1] Marchand and Scheerer state that the density of copper wires is increased by drawing. The wire for which they found this result had density between 8.895 and 8.896, and must therefore have been of different copper from the wires I used. Moreover, the changes due to drawing appear only in the third decimal place, and are so irregular that their conclusions appear hardly justifiable. Marchand and Scheerer, Journal für praktische Chemie, 27, p. 193. 1842.

1. As regards external conditions: (*a*) The temperature at which the different determinations were made varied between 19° and 23° C. The variation of the rigidity modulus between these temperatures is within the limits of error of my determinations, as shown by the experiments of Kohlrausch and Loomis,[1] of Pisati,[2] and of Katzenelsohn.[3] (*b*) The weights hung on the wire were not always the same, so that the condition as regards longitudinal stress varied between 4.8×10^8 and 11.2×10^8 dynes per square cm. The variation in modulus of rigidity due to this cause is also within the limits of experimental error, as shown by my work on the dependence of modulus of torsion on tension.[4] The condition of the wire as regards torsion of course varied during each swing, but this had no appreciable effect, as shown by the fact that the swings were sensibly isochronous. The amplitude was always kept less than 10°.

2. Homogeneity of the wires can not be assumed, so that the values obtained for F must be taken as integrated values for the cross section of each wire. Probably the copper itself was in fact not homogeneous; besides that there was always a film of oxide on the surface of the wire, which could not be entirely gotten rid of. After annealing, the surface was cleaned with HCl, which was then washed off with water, leaving the surface perfectly clean; but it soon became tarnished by exposure to the air.

3. Suppose the body to which the wire is clamped at the bottom not to be perfectly firm, the top being perfectly firm; then the motion of the body at the bottom will approximate to that of a body of very great moment of inertia, hung on to the bottom of the wire, and free to twist with the wire. The motion of such a system will be given by the equations

$$\left.\begin{aligned} \frac{d^2\theta}{dt^2} &= -\frac{M}{K_1}\left[\theta + (\theta - \varphi)\right] = \frac{M}{K_1}(\varphi - 2\theta) \\ \frac{d^2\varphi}{dt^2} &= +\frac{M}{K_2}(\theta - \varphi) \end{aligned}\right\} \qquad (3)$$

where M is the direction-force of the wire, K_1 and K_2 are the moments

[1] Kohlrausch and Loomis, Pogg. Ann., 141, 1870.
[2] Pisati, Nuovo Cimento, V., pp. 145–150.
[3] Katzenelsohn, Beiblätter der Physik, 12, p. 307.
[4] Phys. Rev., Vol. XII., pp. 100–114, 1901.

of inertia of the disk and the body at the bottom respectively, and θ and φ are the respective angular displacements. The elimination of φ gives

$$\frac{d^4\theta}{dt^2} + \left(\frac{M}{K_2} + 2\right)\frac{d^2\theta}{dt^2} + \frac{M}{K_1 K_2}\theta = 0. \tag{4}$$

If initial conditions $\theta = 0$, $\varphi = 0$, $\frac{d\theta}{dt} = \omega$, and $\frac{d\varphi}{dt} = 0$, are assumed, the solution of this equation takes the form

$$\theta = c_1 \sin c_2 t + c_3 \sin c_4 t \tag{5}$$

where c_1, c_2, c_3 and c_4 are constants depending on M, K_1, K_2 and ω, and c_3 is very much smaller than c_1 if K_2 is very much larger than K_1. This shows that the average period taken for a large number of swings will not be affected by a slight lack of rigidity of the support; for $c_3 \sin c_4 t$ will be negative as often as it is positive, and the disk will therefore swing through its position of rest too soon as often as it will do so too late.

4. As regards the shape of the wire: (*a*) It is safe to assume that its cross section is the same at all points of its length, as the die-plate through which the wire is drawn is of very much harder material than the wire, and would not wear away appreciably during the drawing of two meters of wire. (*b*) The wire is always more or less bent, so that its axis not a straight line, but a curve of double curvature. That such deviation from straightness had no appreciable effect in my experiments, I proved empirically by purposely bending and kinking a wire and then determining the period of torsional swing, which was found not to differ from that of the straight wire. (*c*) It is possible that the cross section may not be perfectly circular. If this is the case, then as a first approximation it can be considered elliptical. Then $\frac{1}{r^4}$ of formula (1) must be replaced by $\frac{1}{2}\frac{1}{ab}\left(\frac{1}{a^2} + \frac{1}{b^2}\right)$, where a and b are the semi-axes of the ellipse. If we set $a = r + \delta$ and $b = r - \delta$, we find that the difference between $\frac{1}{r^4}$ and $\frac{1}{2}\frac{1}{ab}\left(\frac{1}{a^2} + \frac{1}{b^2}\right)$ is of the order of δ^2. The error in assuming that the

cross section is circular will be less than 0.1 per cent. if δ is less than $\frac{1}{32}r$; and δ was less than $\frac{1}{32}r$ for all the wires I used, as shown by micrometer calipers; so that this source of error need not be feared.

Determination of Young's Modulus.

To determine Young's modulus the sinking of the lower end of the wire (see Fig. 5) under a known increase of load was read with a micrometer. The lower end of the wire was left free, except that it was prevented from swinging to the side by means of three strings at right angles to the wire, so arranged that they did not interfere with its vertical motion. Young's modulus was given by the formula

$$Y = \frac{sgl}{\pi r^2 e}, \tag{5}$$

where s is the mass of the weights added, g the acceleration of gravity, l the length of the wire, r its radius, and e the increase in length due to the weights added. If we put $r = \sqrt{\frac{m}{\pi l \sigma}}$, where m is the mass of wire, and σ its density, we have

$$Y = \frac{sgl^2\sigma}{me}. \tag{6}$$

The method of determination and the errors of l, σ, and m have already been discussed (see p. 240). s was determined within an error of 0.01 per cent. by direct weighing. To determine e, a succession of readings with the micrometer was taken as the wire was successively loaded and unloaded. The mean values were used; a correction had to be made for the sinking of the upper support, which was measured by the micrometer. The probable error of the final value of e was ± 0.0007 cm., or from 0.4 per cent. to 1 per cent. The combination of these errors gives the probable error of Y between 0.5 per cent. and 1 per cent.

The formula (6) assumes (1) constant external conditions, (2) homogeneity of the wire, (3) cylindrical shape of the wire and (4) the applicability of Hooke's law.

1. The temperature varied between 19° and 23° C. The varaition of Young's modulus within these temperatures is negligible, according to the experiments of Katzenelsohn.[1] The fact that the values obtained are those for isothermal extension has already been noticed.

2. Homogeneity of the wire can not be assumed; the values of Y are to be regarded as average values for any cross section of the wire.

3. The shape of the cross section or the wire is immaterial, as that is eliminated in formula (6). The cross section must, however, be the same at all points of the length of the wire; this can be assumed to be the case with a drawn wire. It is possible that the wire may deviate from straightness; if so, it is to be expected that the wire will be partially straightened by increasing the load, so that the lower end will sink more than if only extension took place. Suppose the half length of the wire to be denoted by λ and suppose the middle of the wire to be at a distance ∂ from the straight line joining its extremities. If a vertical force W be applied to the end of the wire, the horizontal force at the middle tending to straighten the wire will be $W \cdot \frac{\partial}{\lambda}$. If the wire is made perfectly straight, its lower end will sink through a distance $2\partial \cdot \cos \cos^{-1} \frac{\partial}{\lambda} = 2\lambda \left(\frac{\partial}{\lambda}\right)^2$. As the wire will not be perfectly straightened by any vertical force, however great, the sinking of the lower end will be less than $2\lambda\left(\frac{\partial}{\lambda}\right)^2$ and the force acting to produce it will be $W\frac{\partial}{\lambda}$, so that the sinking produced will be of the third (or higher) order of small quantities if $\frac{\partial}{\lambda}$ is of the first order.

4. With the stresses used some slight deviation from Hooke's law is to be expected, according to the experiments of J. O. Thomson.[2] The limits of stress between which my determinations of Young's modulus were made, were approximately the same for all the wires, so that the results will serve for purposes of comparison.

[1] Katzenelsohn, Beiblätter der Physik., 12, 307.
[2] J. O. Thomson, Wied. Ann., 44, 555, 1891.

Determinations of Young's Modulus by Flexure.

The determinations of Young's modulus by bending were made by laying a piece of the wire across two knife-edges which were rigidly braced at a distance of 7.22 ± 0.01 cm. from each other. Exactly midway between the knife-edges a light scale-pan was suspended, on which weights were laid, and the sinking of the middle of the wire was measured with a micrometer. The weights were so arranged that the sinking always amounted to about 0.08 cm. The sinking of the supports was subtracted; and any possible rolling of the wire on the knife-edges was prevented by bending down one end of the wire and letting it rest against a nail, friction being minimized by lubrication. For these experiments the wires were made as straight as possible; but perfect straightness is extremely difficult to attain without subjecting the wire to processes (such as drawing or hammering) which would change its elastic properties. It is obvious that slight deviation from straightness will cause but slight error. No rigorous solution of the problem of the bending of a rod of any initial shape has yet been made.

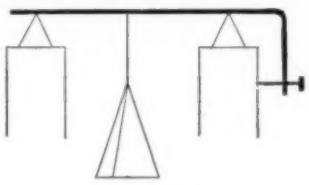


Fig. 7.

The value of Young's modulus (Y_b) is calculated from the formula

$$Y_b = \frac{b^3 g P}{12\pi r^4 h}, \qquad (7)$$

where b is the distance between the knife-edges, g is the acceleration of gravity, P the mass of the weights hung on, r the radius of the wire, and h the depression of the middle.

The probable errors of these quantities are as follows:

b,	$\pm$ 0.01 cm.	or $\pm$ 0.2 per cent.
P,	$\pm$ 0.1 mg.	or $\pm$ 0.0001 per cent.
r,	$\pm$ 0.00005 cm.	or $\pm$ 0.1 per cent.
h,	$\pm$ 0.0006 cm.	or $\pm$ 0.6 per cent.

giving for the probable error of the result $\pm$ 1 per cent.

Physical Laboratory, Princeton University.

THE ABSORPTION SPECTRUM OF COLLOID FERRIC HYDRATE.

BY B. E. MOORE.

IN a recent article upon "A Spectrophotometric Study of the Hydrolysis of Ferric Chloride,"[1] I have pointed out that the probable final product of hydrolysis, $x(FeO_3H_3)$, could be advantageously compared with Graham's colloid ferric hydrate. For, if two solutions of the same base should have identical absorption spectra, it would be natural to assume the same structure of the molecule.

A solution of colloid ferric hydrate was prepared according to Graham's direction. After dialyzing for five weeks, the solution was kindly tested by Mr. R. W. Thatcher who found it to be .1116 normal with respect to iron and that 90.4 per cent. of the chlorine had been removed. From a sample of this solution I prepared a dilute solution, .002462 normal, and another solution of the same concentration from the stock of ferric chloride made twelve months previous. These solutions were placed in two absorption cells of identical absorption coefficients. One cell was placed before each slit,[2] and ten readings of the slit were taken at a definite point in the spectrum. The cells were then interchanged, and ten new readings taken. Similar readings were taken at other points in the spectrum. A comparison of these sets of readings gives double the relative difference of absorption. This method was particularly good at points in the spectrum where absorption differences were small. When the absorption differences were large, in one position the slit must be opened very wide, which necessitated its abandonment. However, the absorption spectra of each could be determined separately as in the previous contribution. This method was also adopted at all

[1] PHYSICAL REVIEW, Vol. 12, p. 151.
[2] PHYSICAL REVIEW, Vol. 12, p. 160.

points in the spectrum as a check. The ferric chloride solution had been hydrolizing for eight days at room temperature and a comparison of its absorption spectrum with the curve for the same concentration in the previous article shows that the hydrolysis would proceed a little farther. However, the general character of the two spectra is the same. But there is a marked difference between the

TABLE.

Transmission in per cent.

	Colloid Ferric Hydrate.			Hydrated Ferric Chloride.
	$n = .002462$.	$n = .001231$.		
	Observed.	Observed.	Calcu.[1]	
6500	89.3	93.6	94.5	82.1
6000	87.6	92.5	93.6	75.2
5750	82.5	89.3	90.8	61.5
5500	71.5	82.	84.5	40.5
5250	41.3	66.8	64.3	19.8
5000	13.25	34.1	36.4	9.4

absorption spectra of these solutions and the absorption spectrum of colloid ferric hydrate, as is shown by the following table of data

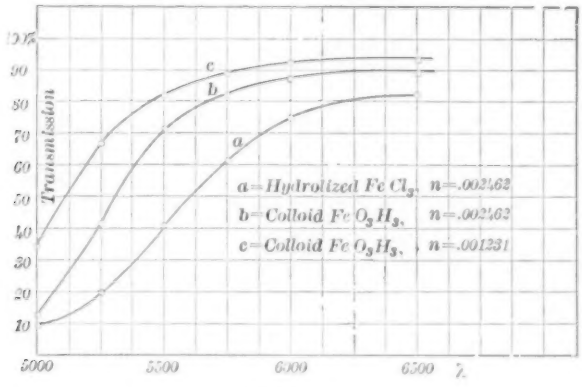


Fig. 8.

and curves. The character of the curves is not the same. The ferric chloride solution absorbs more throughout the spectrum, but

[1] Calculated from formula $\text{colog } i_2 = -\frac{\text{colog } i_1}{2}$, where the intensities, i_1 for $n = .002462$ are assumed correct.

relatively more in the red. The curve for the colloid absorption is much steeper as it approaches the region of strong absorption so that it would intersect several of the previous curves[1] for solutions of the hydrolized ferric chloride. This fact excludes the assumption of the same product but diluter solution. It leaves us two other assumptions. We may assume with Antoni and Giglio, that in the process of transformation there is a combination of iron, chlorine and hydroxyl; or we may assume there is present an appreciable amount of crystalloid ferric hydrate in the colloid hydrate prepared by dialysis. Small quantities of the crystalloid are expected to be present in the colloid solution but the difference in the absorption spectra would necessitate the assumption of larger quantities of the crystalloid than I had anticipated. However, for reasons previously given, I think the latter view more tenable than the first assumption. The nine per cent. chlorine is not responsible for the difference, since in the hydrolized ferric chloride there may be as much as thirteen per cent. of the ferric chloride not transformed.

I now prepared a dilute solution of colloid ferric hydrate and replaced 5 cu. cm. of 90 cu. cm. of water with 5 cu. cm. of strong chlorine water, and compared this solution at different points in the spectrum with the previously prepared solution of colloid ferric hydrate. Tests made at different times during two weeks' interval showed no difference whatsoever. A solution of hydrochloric acid whose density was 1.163 at 25° C. was diluted 100 fold and 5 cu. cm. of this diluted acid replaced 5 cu. cm. of water as before. At different times for two weeks, this solution was compared with the two previous ones and at no time was there a difference observed which could not be attributed to working conditions. That is, neither the chlorine caused the formation of any chlorine products nor the hydrogen effected any transformation of the possible crystalloids. The introduction of 5 cu. cm. of Graham's colloid ferric hydrate into a fresh prepared solution of ferric chloride accelerated the hydrolysis[2] so that in two hours the solution was as dark as the older solution of the same concentration had become upon standing for four hours. Next, 5 cu. cm. of an old solution of

[1] Previous contribution, Fig. 5, p. 175.
[2] Goodwin, PHYS. REV., Vol. 11, p. 193.

hydrolized ferric chloride was added to a new solution and at the end of two hours, the mixed solution was as dark as the old solution had become at the end of 5.5 hours. All the solutions in this test were of the same concentration, viz.: .002462 normal. The action indicates that the accelerators are the same in the two cases but that there is a larger quantity of it present in the hydrolized ferric chloride than there is in the dialyzed ferric hydrate. The two were of the same concentration as to iron and the slower acceleration of the Graham's colloid ferric hydrate can be readily explained upon the assumption previously made of appreciable quantities of inactive crystalloid hydrate. The absorption curves then suggest that the colloid absorption spectrum lies between the hydrolized ferric hydrate and the ferric chloride spectra.

PHYSICAL LABORATORY,
UNIVERSITY OF NEBRASKA, July, 1901.

THE ABSOLUTE MEASUREMENT OF SELF-INDUCTANCE.

BY WILLIAM DUANE.

THE author has found the following to be a relatively easy method of measuring the absolute value of the self-inductance of a coil without using a standard of self-inductance or of capacity.

Suppose the coil is wound in two parts. Let the mutual inductance of the two parts be M; the self-inductance of one be L_1; and, of the other L_2. Then, if the current flows in the same direction through both coils in series the self-inductance of the whole is

$$L' = L_1 + 2M + L_2. \tag{1}$$

If the current flows in opposite directions through both coils in series the self-inductance of the whole is

$$L'' = L_1 - 2M + L_2. \tag{2}$$

In the first part of the method the ratio of L' to L'' is measured by comparing each with a third self-inductance L, which should be of the order of magnitude of L' and L''. Any of the methods of comparing self inductances can be used. The measurement gives us

$$L' = k_1 L$$

$$L'' = k_2 L,$$

and therefore

$$\frac{L'}{L''} = \frac{k_1}{k_2} = A, \tag{3}$$

where A is a known quantity.

In the second part of the method the value of the mutual inductance M is measured. This can be done by any of the usual methods (for example the earth inductor and ballistic galvanometer,

or the doubly wound solinoid and ballistic galvanometer method) and is a comparatively easy measurement. From equations (1) and (2) we have

$$L' - L'' = 4M. \tag{4}$$

From (3) and (4)

$$L' = \frac{4MA}{A - 1} \tag{5}$$

and

$$L'' = \frac{4M}{A - 1} \tag{6}$$

which gives us L' and L'' in terms of measured quantities.

In order to use the above method it is necessary to be able to break the circuit of the coil at some point inside of it. This can be done best during the winding, and the author suggests that all coils that are to be used as standards of self-inductance be wound in two sections, so that their values can be easily checked from time to time.

It is not desirable to break the coil in such a way that the mutual inductance is small, for in that case L' and L'' would be very nearly equal, A would not differ much from unity, and any errors in the measurement of A would be greatly magnified when it is substituted in the formulas (5) and (6).

On the other hand it is not desirable (at least when the coils are circular, such as are often made and sold as standards) to break the coil in the middle, for then $M = L_1 = L_2$ approximately and L'' would be very small. The best method of winding lies between these two, the exact division of the coil depending on the relative accuracy of the methods used to measure A and M.

If the coil to be measured is not wound so as to be broken conveniently, its self-inductance can be measured by means of the above method slightly modified. Let L_1 be its self-inductance. Join in series with it another coil of self-inductance L_2, which should be of the same order of magnitude as L_1 and place the two near together so that their mutual inductance is M. Then, considering the two coils as one circuit, measure its self-inductance,

$$L' = L_1 + L_2 + 2M$$

as above.

We have from this equation

$$L_1 + L_2 = L' - 2M = B \tag{7}$$

a determined quantity.

It is now necessary only to measure the ratio of L_2 to L_1, in order to determine their values.

We have

$$\frac{L_2}{L_1} = C \tag{8}$$

a measured quantity. Hence from (7) and (8)

$$L_1 = \frac{B}{1 + C}.$$

and

$$L_2 = \frac{BC}{1 + C}.$$

The above remarks as to the best relative magnitudes of L_1 and L for accurate work apply to this case, also.

It is necessary of course that the two coils should retain their relative position during the entire measurement of L_1, otherwise the mutual inductance M would vary.

The members of my class in electrical measurements have tested the above method, and obtained very consistent results. It gives me great pleasure to thank them for the care with which they have performed the tests.

HALE PHYSICAL LABORATORY,
UNIVERSITY OF COLORADO.

NEW BOOKS.

The Fifth and Sixth Books of Euclid. By M. J. M. Hill, F.R.S., Professor at University College, London. Cambridge University Press.

Many of the "Euclids" retain a little of the form of the real Euclid, but replace its rigorous logic by reasoning which often fails to be conclusive. The present work is a refreshing contrast to these in spirit and methods; the proofs are in general not open to question and where an assumption is necessary there is no attempt to get around it by specious reasoning, but the statement that it is an assumption is plainly made. Especially in the first pages, where a foundation is laid for the work which follows, is the desire of the author for rigorous methods apparent.

The book is intended as an elementary text-book, covering the ground of the fifth and sixth books of Euclid; its object, as the author expresses it, is "to remove the chief difficulties felt by those who desire to understand the sixth book." The fifth book is made subservient to this object and there is no attempt in it to follow Euclid; the method of treatment employed dispenses with ratio except as a secondary consideration, and is new in the sense of now being published for the first time in text-book form. The attempt of the author to lead up to the sixth book by an easier path than that of ratio is undoubtedly successful, yet the work is hardly of a grade for beginners, the reason being that a satisfactory treatment of either ratio or subjects nearly related to it involves reasoning too close to be comprehended without preparation.

One of the chief difficulties of ratio to the student is that the definition does not tell him what the thing is, and, although he may have an idea of it, the lack of definiteness makes him feel that he is dealing with something elusive. Professor Hill ingeniously avoids this difficulty by using for the foundation of his work a substitute for ratio called the "relative multiple scale"; this is defined with exactness and is easy of comprehension, yet serves in the sixth book as well as ratio; it is indeed closely related to ratio, the sameness of two "scales" leading to the same results as the sameness of two ratios. The "multiple scale" may be described briefly as a device for showing graphically whether the multiple r of the magnitude A is greater than, equal to, or less than the multiple s of the magnitude B.

The first pages of the book are devoted to an explanation of the "multiple scale" and to proving some of its properties. Then certain applications are taken up and the word ratio is introduced cautiously by means of dual statements of propositions, "ratio" being used in the secondary form. A little later a chapter is devoted to ratio in which it is pointed out that the earlier propositions regarding the multiple scale correspond to ideas of ratio already held by the student. Thus he is "led to the idea that two magnitudes of the same kind determine not only a relative multiple scale but also a ratio." That is, the student gains a considerable empirical knowledge of ratio although the proofs rest strictly upon the multiple scale.

It is unfortunate that the author has made a few exceptions to the rule that the multiple scale should be fundamental and ratio subsidiary; in some of these the difference consists chiefly in the form of statement and but little harm is done beyond the marring of the consistency of the book; in one or two, however, as in dealing with duplicate ratio, propositions are made to depend on ratio alone—to this the objections on the ground of mathematical rigor are more serious. In judging of them, however, the limitations imposed by the fact that the book is a text-book and the utter lack of rigor in most text-books should be remembered.

As in all elementary mathematical works assumptions have been necessary, and the author has frankly pointed out the more important ones to the student; his sound position in this is not so common that it should be passed over without comment.

WENDELL M. STRONG.

NEW YORK, August, 1901.

Leitfaden der Wetterkunde. By Dr. R. BÖRNSTEIN. 8vo, pp. vi + 181. Braunschweig, Vieweg und Sohn, 1901.

This is an elementary text book-on meteorology but it contains many matters of interest to the physicist. The author defines meteorology in his opening chapter as the physics of the atmosphere. He takes up first of all the composition of the air, and then proceeds to consider in turn the six meteorological elements, *temperature*, *moisture*, *cloudiness*, *precipitation*, *barometric temperature* and *wind*. The daily and yearly temperature range in various localities is briefly discussed and the influence upon the same of radiation from the soil, of neighboring bodies of water and of ocean currents such as the gulf stream are shown by means of well-selected curves, the data for which are chiefly taken from German sources.

The chapter on clouds is particularly interesting. It is illustrated by means of a set of colored photographic plates of great beauty which serve better than any description to enable the layman to identify and

recognize the various types of clouds. Here as elsewhere throughout the volume the treatment of even important topics is of extreme brevity; to the methods of studying the movements and the heights of clouds, for example, a single paragraph is given. Frequent citations of original sources are made, by means of consecutively-numbered references, to a bibliography which is gathered in a separate section at the close of the volume. This list contains 206 titles and includes many of the most important memoirs of the science.

The chapter on precipitation deals with dew, various forms of frost, and with rain, snow and hail. Here as elsewhere the statistical portion of the subject is reduced to a minimum. The author makes use of it, indeed, chiefly to illustrate such general principles as may be regarded as well established concerning the influence of the sea, of mountain chains and of forests.

The discussion of these six elements occupies the first 94 pages of Professor Börnstein's book. It is followed by a somewhat fuller treatise upon the weather, which is considered as the result of the mutual action of these meteorological elements. In this chapter movements of the atmosphere, with the attendant changes of pressure which accompany storms, are discussed at considerable length. The data are chiefly from European sources. Under the head of weather-bureau service the systems employed in various countries are briefly summarized.

In so short a treatise, and especially in one written merely as an outline of the elements of a science, many things must of necessity be left out. The most striking omission in this book is perhaps the failure to describe the numerous ingenious recording devices that have come into use in modern weather-bureaus. The omission is doubtless entirely justifiable, but one is disappointed nevertheless. In whatever he undertakes to discuss, however, the author is admirably simple, concise, clear and accurate.

E. L. N.

Induction Coils, How to Make, Use and Repair Them. By H. S. NORRIE. (NORMAN H. SCHNEIDER.) Second Edition. Pp. xvi + 269. New York, Spon & Chamberlain, 1901.

This new edition of Mr. Schneider's little handbook has in addition to the contents of the original edition, brief descriptions of coils for gas and automobile engines, medical coils, new forms of contact breakers, electric gas-lighting apparatus and batteries. There is a short chapter on wireless telegraphy with diagrams of the arrangement of the transmitting and receiving apparatus, in which several forms of coherer are briefly described. The treatment in this chapter as throughout the book is of the sort termed *practical*, that is to say explicit directions are given

by means of which any handy individual can construct for himself the simpler parts of the apparatus described. The chief value of the book consists in the fact that it gives actual specifications for the construction of the various pieces of apparatus described; indicating the number of turns and the size of wire, nature of the insulation and indeed going into the numerous details which are necessary to successful operation and which are rarely to be found in works in which the attention is directed chiefly to the theory and principles of the subject.

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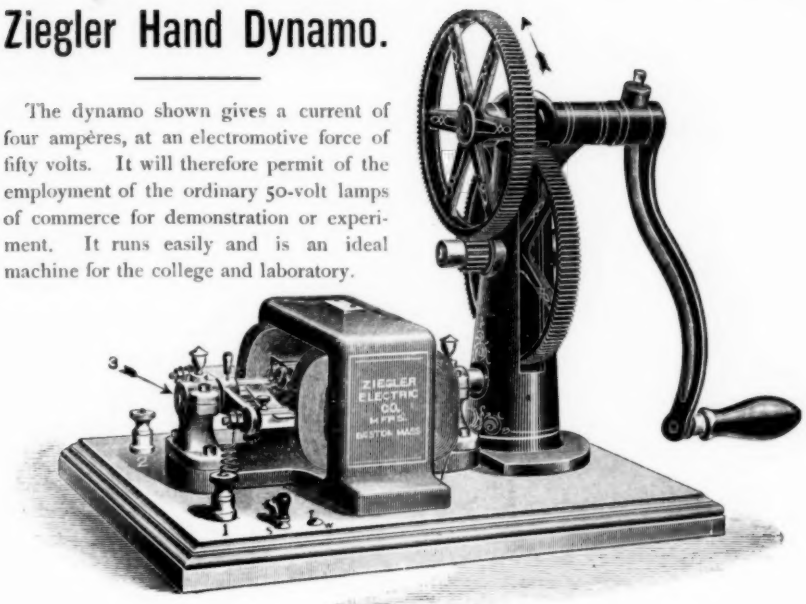

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